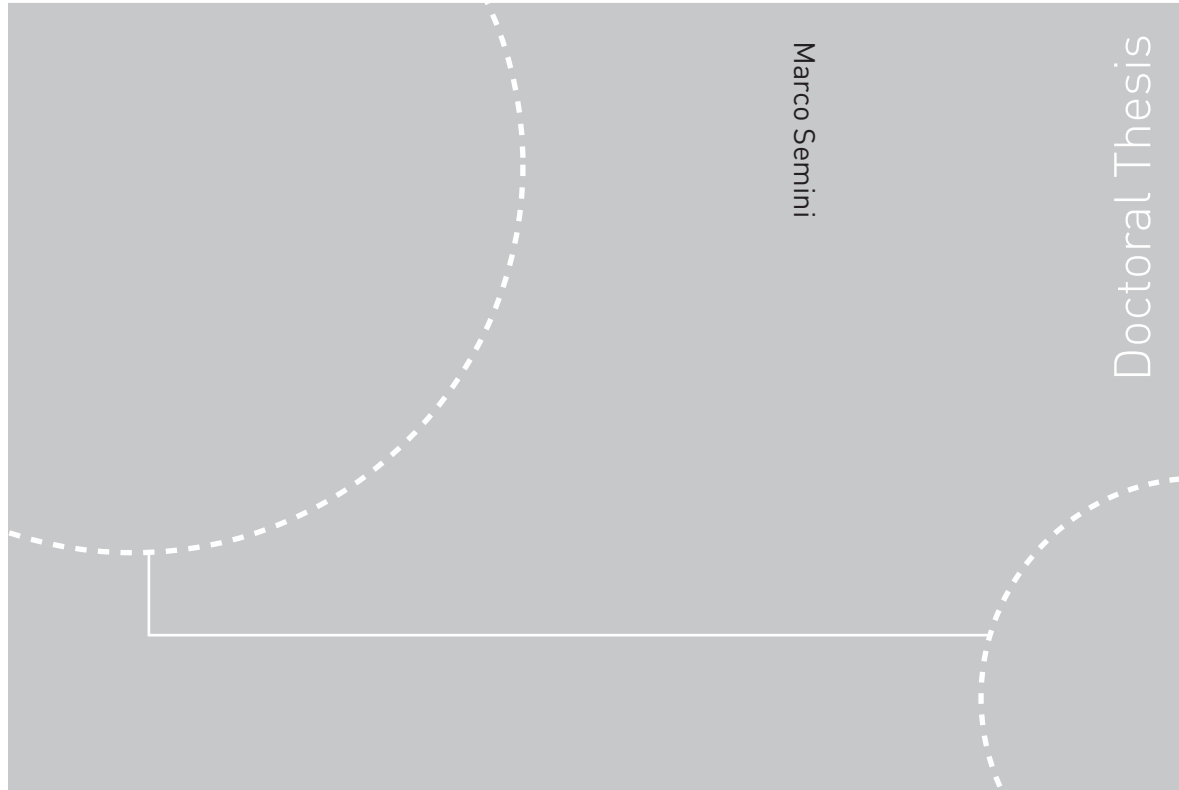


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Marco Semini

Applicability of Operations Research in Manufacturing Logistics



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Trondheim, February 2011

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Abstract

Ever-increasing customer expectations and fierce competition in global markets force manufacturing companies to continuously enhance competitiveness to stay profitable. In recent years, they have realized that manufacturing logistics, i.e. the management of material and information flows in manufacturing companies, has a considerable potential to reduce costs, improve customer service and provide them with a competitive advantage. Manufacturing logistics decision-making is, however, a complex and difficult task, and logistics professionals therefore continuously seek approaches and tools that help them take better decisions. One such approach is operations research (OR), which develops quantitative models and analyzes them to draw some conclusions about the model and, consequently, about the real world. OR has successfully supported manufacturing logistics for decades. It covers a wide variety of techniques, each with its strengths, limitations, success stories and group of advocates. They work well in certain situations, but none of them is a panacea that solves every problem. For logistics decision-makers, it is therefore crucial to understand the problem situations in which the different OR technique can provide added value, i.e. how applicable OR techniques are in different contexts. Research has shown that a mismatch between problem and model/technique is a frequent reason for failure of OR initiatives. There is also a considerable gap between the models and techniques described in the literature and those actually used for decision support in practice, which further emphasizes the need to understand their applicability, i.e. how useful they are in different situations.

A review of the literature revealed, however, that relatively little research has aimed to increase the understanding of the applicability of OR techniques. There is a paucity of literature providing details about the situations in which the techniques work well and there is relatively little guidance on selecting techniques. In practice, there seems to be considerable confusion and disagreement. Technique selection is in danger of being affected by personal preferences, and logistics professionals without OR background have little means to judge technique appropriateness.

The present thesis addresses these weaknesses in research and practice from the perspective of the operations management and logistics fields, which are concerned with effective decision-making in operations/logistics. The thesis' overall objective is to increase knowledge on the applicability of OR techniques to support decision-making in manufacturing logistics, and to provide an overview of such knowledge for logistics professionals without OR background. This overall objective is achieved by means of three specific objectives: 1. To identify, classify and characterize the typical OR techniques used to support manufacturing logistics in practice, and to identify and classify the typical manufacturing logistics decisions supported by OR techniques. 2. To provide empirical evidence of how the applicability of OR techniques depends on different problem situation characteristics. 3. To develop guidelines that help logistics professionals understand if and how OR techniques can support a given real-world problem situation.

The overall methodological idea to achieve these objectives was to study a large number of successful OR applications, identify the areas in which the different OR techniques were useful, investigate how they were used, and develop guidelines based on findings and existing knowledge on OR applicability. Since literature contains hundreds of descriptions of OR applications, with details about the situations in which they took place, it was deemed appropriate to rely heavily on secondary literature. Two extensive surveys of successful applications described in the literature were carried out, one of the journal *Interfaces*, the

other of *Winter Simulation Conference* proceedings. For a greater in-depth understanding, three case studies were performed as well. This provided a sample of close to 200 OR applications, which constituted the thesis' empirical foundation. Thesis results were obtained by synthesizing this empirical data with existing literature and the researcher's background and experience.

The main results of this thesis are as follows. (1) A classification of the main OR techniques used to support manufacturing logistics, namely deterministic optimization, discrete-event simulation, queuing theory and inventory theory. At such a high level of technique distinction, different techniques have different world views, provide decision support in different ways, are often practised by different people and are implemented in different types of software systems. At this level, technique selection is therefore of interest and importance not only to OR professionals, but also to logistics professionals responsible of taking sound decisions and seeking decision support. The thesis also includes a characterization of these techniques, based on the idea of paradigms, providing a general understanding of each technique's key assumptions and properties.

(2) A classification of manufacturing logistics decisions supported by OR, including short-term production planning/scheduling; plant location and distribution system design; production plant design; aggregate production and capacity planning; inventory management; the determination of production rules/policies; and transportation management. Integrated into a seven-by-four matrix, the two classifications provide a framework for systematic investigations of the applicability of OR techniques in manufacturing logistics.

(3) Substantial empirical evidence of the link between problem situation characteristics and OR usage. Focus is on five characteristics that seem to affect OR technique applicability, namely decision type, planning horizon, system scope, company size and industry. Empirical evidence was obtained from the two surveys performed as a part of this doctorate study, as well as from relevant surveys carried out by other researchers. The evidence is used to test claims made in the literature about the applicability of OR, as well as to put forward several new propositions. Additional empirical evidence of how problem situation characteristics affect technique applicability was obtained from the three case studies. In the first, Felleskjøpet Trondheim used deterministic optimization to support plant location and distribution system design; in the second, Gilde Norsk Kjøtt used discrete-event simulation to support production plant design and to determine production rules/policies; in the third, Mustad assessed the potential of multi-echelon inventory theory to reduce safety stocks in its global logistics network.

(4) Extensive guidelines on the applicability of OR techniques in manufacturing logistics. For the seven decision types typically supported by OR, these guidelines discuss OR technique applicability and provide links from detailed problem situation characteristics to suitable OR techniques. Furthermore, they contain descriptions of how OR techniques support the different decision types, with focus on practice-relevant issues such as input data requirements, the way the models are used in decision-making, relevant types of software systems, time/resource requirements etc. This provides an understanding of how OR works. Given a real-world problem situation in manufacturing logistics, the guidelines thus help assess if OR techniques can provide added value. They target people who need to be aware of the opportunities of OR without being OR professionals, such as logistics and operations managers. They are presented in a form and language that is relevant for this audience, without mathematics or computer jargon. Still, they can also be of interest to OR

professionals, especially those new to the field; they highlighting promising application areas and contain structured references to hundreds of real-world OR applications described in the literature. The use and usefulness of the guidelines is illustrated by means of a real-world situation where they could have made OR technique selection more effective.

This thesis contributes to a theory of the practice of OR. The main benefits expected are less confusion about the areas in which OR techniques work well, more effective technique selection in practice, and increased exploitation of the opportunities of OR to support manufacturing logistics. Hopefully, it counteracts frequently returning discussions and even argument about the appropriateness of discrete-event simulation as opposed to optimization in logistics and supply chain management. Ultimately, such benefits will lead to more effective decision-making in manufacturing companies. For the research community, the thesis highlights practically relevant topics for future model development; it pinpoints areas in which further research is required to close the gap between theory and practice; and it can serve as a solid foundation for future research on OR applicability.

Sammendrag

Denne avhandlingen undersøker bruken av operasjonsanalytiske teknikker for beslutningsstøtte i produksjonslogistikk. Produksjonslogistikk har som oppgave å designe, planlegge og styre material- og informasjonsflyten i produksjonsbedrifter og deres verdikjeder. I operasjonsanalyse utvikles og analyseres kvantitative modeller for å øke forståelsen av komplekse problemstillinger i virkeligheten. Det er et samlebegrep for en rekke forskjellige modelleringsteknikker, som alle har sine styrker, begrensninger, suksesshistorier og tilhengere. Flere har hatt en lang rekke anvendelser i produksjonslogistikk, og ført til betydelige kostnadsbesparelser, økt effektivitet og bedre kundeservice. Samtidig har forskning vist at samsvar mellom beslutningssituasjon og teknikk er en viktig forutsetning for å lykkes med slike anvendelser. For beslutningstakere i produksjon og logistikk er det dermed viktig å forstå i hvilke situasjoner de ulike teknikkene er anvendelige. Det er også mange modeller beskrevet i forskningslitteraturen som hittil ikke har blitt brukt til beslutningstaking i virkeligheten. Likevel er det lite forskning som undersøker modellenes og teknikkenes anvendelighet, og det er en del forvirring rundt deres bruksområder, ikke minst blant beslutningstakere i industrien, som ofte ikke har operasjonsanalytisk bakgrunn.

Målet med denne avhandlingen er derfor å øke kunnskapen om operasjonsanalytiske teknikkers anvendelighet i produksjonslogistikk, og å formidle denne kunnskapen fra et ledersperspektiv. Hensikten er at dette skal føre til mer klarhet rundt operasjonsanalysens muligheter og begrensninger, mer effektiv vurdering av hvor egnet de ulike teknikkene er i en beslutningssituasjon, og økt utnyttelse av deres potensial. Den forskningsmetodiske tilnærmingen for å nå dette målet har vært å studere et stort antall vellykkede anvendelser av operasjonsanalytiske teknikker, å identifisere i hvilke situasjoner de ulike teknikkene har vært nyttige, å undersøke hvordan de har blitt brukt og å utvikle retningslinjer basert på funnene og relevant eksisterende kunnskap. Det empiriske grunnlaget i doktorgradsstudiet består av cirka 200 anvendelser beskrevet i litteraturen, pluss tre case studier for mer dyptgående analyse.

Studiet har ført til følgende resultater:

- (1) En klassifisering av de fire teknikkene som har stått for de fleste anvendelsene av operasjonsanalyse i produksjonslogistikk: *Deterministisk optimering, diskret-hendelsessimulering, køteori og lagerteori*. Det gis en paradigmatisk fremstilling av disse teknikkene for å synliggjøre og sammenligne nøkkelegenskaper og funksjonsmåter.
- (2) En overordnet gruppering av beslutningene som har blitt støttet av operasjonsanalyse, i følgende sju beslutningstyper: *Fabrikklokalisering og design av distribusjonsnettverket, fabrikkdesign, mellomlangsigtig produksjons- og kapasitetsplanlegging, transportplanlegging- og styring, lagerstyring, valg av regler og prinsipper relatert til produksjonsstyring, og kortsiktig produksjonsplanlegging*.
- (3) En analyse og diskusjon av sammenhengen mellom beslutningssituasjon og bruken av ulike operasjonsanalytiske teknikker, basert på studiets empiriske grunnlag. Fokus er på følgende egenskaper ved beslutningssituasjoner: *Beslutningstype, planleggingshorisont, systemgrenser, bedriftsstørrelse og bransje*.
- (4) Retningslinjer som skal hjelpe med å forstå hvilke beslutningssituasjoner som kan dra nytte av hvilke teknikker. Retningslinjene beskriver også hvordan teknikkene kan støtte disse situasjonene, med fokus på tema som er relevante for praksis. Retningslinjene og avhandlingen mer generelt henvender seg primært til personer som trenger å forstå mulighetene som ligger i kvantitative modeller uten å være operasjonsanalytikere selv. Avhandlingen bør også være av interesse for operasjonsanalytikere, blant annet ved at den synliggjør lovende anvendelsesområder for de ulike teknikkene.

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PART I - INTRODUCTION

1 Introduction

1.1 Challenging logistics decision-making

Ever-increasing customer expectations and fierce competition in global markets force companies to continuously enhance competitiveness to stay profitable. In order to succeed, they must be able to reduce costs and at the same time increase customer service (Christopher 2005). New technology, alongside with conceptual and methodological advances, provide the means necessary to achieve this goal.

One business area that has received particular attention in recent years is logistics, i.e. the management of material flows and related information flows. Even though logistics has been a decisive activity in the military throughout the history of mankind, it is only in the recent past that companies have truly recognized the impact logistics can have to achieve competitive advantage (Christopher 2005, Frazelle 2002). Today, it is considered one of the most important activities in modern societies (Ghiani et al. 2004). Both in the EU and the USA, total logistics costs represent over 10% of the Gross Domestic Product (Ghiani et al. 2004, Frazelle 2002, respectively). In addition to cost reduction, the recent focus on logistics is motivated by an understanding that logistics can provide an important competitive advantage (Christopher 2005, Bowersox et al. 2002). Companies that have developed effective and efficient logistics processes achieve superior customer service at minimum cost. One of the key advantages of focusing on logistics lies in precisely its ability to simultaneously reduce costs and improve customer service.

However, making the right choices and decisions in logistics is a difficult task. The difficulty can be attributed to the complexity and uncertainties inherent in most logistics systems (Simchi-Levi et al. 2008). Typically, they consist of:

- Hundreds or thousands of products with different operational characteristics
- Numerous suppliers, customers, warehouses, plants and transportation links all across the globe
- Numerous resources with different characteristics, such as machines, equipment, manpower, IT systems etc.
- High uncertainties, both in demand, internal processes and supplies
- Considerable variability over time, such as demand seasonality, trends, promotions etc.
- Continuous evolvement over time due to, for example, increasing customer power
- Complex flows of materials, information, and capital
- Complex systems of principles, rules and policies used to manage these flows
- Different entities with different, conflicting objectives

With such complexities and uncertainties, taking decisions that lead to effective and efficient logistics solutions is clearly a daunting task.

Logistics is a key activity in both manufacturing and service companies. This thesis focuses on logistics in the former: *Manufacturing logistics*. The focus in manufacturing logistics is on transformation of material, and how this transformation can be done effectively and according to customer requirements. A key feature of manufacturing logistics is that material/information flows are considered from the manufacturer's perspective. The goal is to make materials and products flow from suppliers through internal operations to the final customer as efficiently and effectively as possible.

1.2 Operations research for decision support

Given the complexity and uncertainty of logistics systems, decision-makers continuously seek approaches and tools that help them take better decisions and improve their logistics processes. Over the years, a plethora of such approaches has developed. Loosely speaking, one may say that each approach constitutes a management philosophy, consisting of principles, guidelines and techniques of varying degrees of formality and complexity. Examples of such approaches include business process reengineering, total quality management, lean manufacturing and statistical process control. Each of these approaches has been successfully applied in practice, and each is cultivated by its own group of advocates. Since resources are limited, companies can implement just a few of these approaches. As a consequence, they are often seen as competing, even though they first and foremost complement each other.

This thesis concentrates on one particular such approach (Figure 1-1): *Operations research*, abbreviated OR. Essentially, OR develops a quantitative model and uses it to perform various analyses and calculations. Over the years, OR has developed a particularly large community of advocates. OR is an umbrella term, covering a wide range of techniques clustered around different types of quantitative models. In logistics and supply chain management, popular techniques include linear programming, discrete-event simulation, queuing theory, and inventory theory (Ghiani et al. 2004).

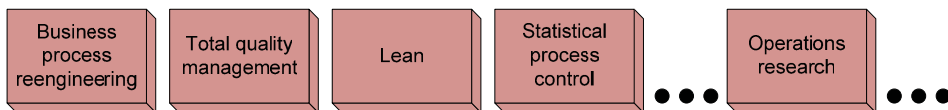


Figure 1-1: OR is one of numerous approaches that can help improve logistics processes.

Logistics can benefit from OR in various contexts. In their simplest forms, decision-makers use quantitative models daily in back-of-the-envelope calculations and spreadsheet applications. More formal OR applications involve one or several OR professionals who develop sophisticated models and carry out advanced analyses using various more or less specific data tools. Sometimes, such OR applications result in user-friendly decision support systems, which are used again and again by decision-makers. Quantitative models are also integrated in many commercially available tools such as inventory management systems and the more recent Advanced Planning and Scheduling (APS) systems. Numerous descriptions of beneficial OR applications in the practitioner-oriented journal *Interfaces* bear witness to the success of OR for decision support in logistics and supply chain management.

The success of OR can be explained by its strengths. OR facilitates understanding of often complex problems, provides a structured approach to problem analysis and constitutes an objective and rational basis for decision-making (Jeffrey and Seaton 1995). Quantitative

models allow quick testing of the effects of various manipulations without having to make changes in the real system (Turban and Aronson 2001). This saves time and money, and it reduces risks. Models enable the analysis of a very large number of possible solutions, and they can recommend suitable courses of action. Models can also facilitate communication and provide a common basis for discussions.

On the other hand, OR has also weaknesses. One such weakness is that it can easily lead to overemphasis of quantifiable aspects. Modelling always necessitates simplification. This can result in analyses that are technically sound, but disregard key knowledge, make unrealistic assumptions, or answer the wrong questions. Woolsey (2006a, 2006b) provides some examples of inappropriate OR use. A further weakness is that stakeholders must agree on objectives and means, otherwise the results of a modelling analysis will not be used for decision-making. For example, stakeholders must agree on the nature of the problem situation, and that a quantitative model can provide added value. Developing and using models also often requires quite some data, time, resources and expertise.

1.3 Research issue

Since OR has both strengths and weaknesses, it is natural to assume that it can provide useful decision support in some contexts, but might be less appropriate in others. At the next lower level, distinguishing between different OR techniques, the same applies: Each technique has its particular properties, advantages and limitations, which affect the circumstances in which it can be applied successfully. For example, different techniques often provide answers to different questions and they differ in the way they represent the real world and support decision-making. Each technique has had its success stories, but none is a panacea that can be applied in all situations. The degree to which OR and its techniques can provide useful decision support – their *applicability* - depends on the real-world context. The question therefore is: In which circumstances can OR and its techniques provide useful decision support? That is, how applicable are they in different real-world contexts?

Understanding the applicability of OR techniques and selecting appropriate ones is not obvious (Murphy 2005a, Flood and Jackson 1991). It requires an in-depth understanding of the OR field, as well as of the particular real-world context considered. As explained above, each OR technique has its own properties, but it can be difficult to grasp which of them are most valuable in a given context. To a certain degree, different techniques may even be compared to Kuhn's (1970) concept of paradigms, where different perspectives or 'world-views' demonstrate a flavour of incommensurability, i.e. they cannot easily be compared and ranked according to suitability criteria. While this thesis takes the stance that a precise understanding of the problem situation often makes technique selection incidental, the comparison with paradigms still illustrates that selecting appropriate techniques can be difficult in practice.

Understanding the applicability of OR techniques is, however, critical for both logistics professionals and OR professionals. The success stories published in *Interfaces* show that applied in the right contexts, OR techniques can provide a distinct competitive advantage. On the other hand, mismatch between problem situation and OR technique is a frequent reason for failure of OR applications in practice (Abdel-Malek et al. 1999, Jeffrey and Seaton 1995, Tilanus 1985). Thus, recognizing where the different OR techniques possess added value is an important prerequisite for successful OR application. This has been emphasized in particular by industrial consultants using OR, such as Mayo and Wichmann (2003) and Fortuin and Zijlstra (2000). Hooker (2007) and Murphy (2005c) stress that lacking understanding of what

OR does and what it can be used for is an important reason why OR is not used in practice more often.

This thesis' research issue is therefore

the applicability of OR and its techniques to support decision-making in manufacturing logistics.

1.4 Research problems and objectives

A literature review revealed that few researchers have addressed this issue. Also other researchers observed that most work in OR literature seems to concentrate on the theoretical development of models and solution algorithms (Murphy 2005c, Pidd and Dunning-Lewis 2001). A number of authors do address OR applicability, but their answers are rather general and do not provide detailed criteria that can be used to determine how appropriate OR techniques are in different contexts. Moreover, their claims have not been validated empirically. OR experts sometimes write about the appropriateness of particular OR techniques, but there is the danger that they exaggerate the applicability of their favourite technique(s).

Lacking research on the applicability of OR techniques is reflected in current practice. Technique selection is frequently regarded as an art (Brooks and Tobias 1996) which can only be mastered by gradual acquisition of experience. Banerjee and Basu (1993) note that model use appears to be carried out in a rather ad hoc way, and Munro and Mingers (2002) and Jeffrey and Seaton (1995) found that methodological choices often are not explicitly reflected on or articulated. Discussions between the advocates of different techniques are not uncommon. For example, discussion and even argument about the appropriateness of simulation as opposed to optimization for logistics and supply chain problems has raged for decades (Powell 2005, Riddalls et al. 2000, Mentzer 1989). Among logistics professionals without OR background, this leads to a lot of confusion. They have usually little means to judge the appropriateness of OR techniques, even though technique choice can significantly affect the kind of decision support they receive.

In summary, the following research gaps related to the applicability of OR techniques in manufacturing logistics have been identified:

- There is relatively little research investigating the contexts in which the different OR techniques OR work well and providing help in selecting appropriate techniques.
- Existing research is often of limited usefulness in practice and has not been validated empirically.
- Technique selection in practice is often ad hoc and in danger of being affected by personal preferences.
- Logistics professionals without OR background have little means to judge the appropriateness of OR techniques, nor are they aware of the implications of choosing a particular technique.

This thesis aims to mitigate these problems within the area of manufacturing logistics. The overall objective is therefore

To increase knowledge on the applicability of OR techniques to support decision-making in manufacturing logistics, and to provide an overview of such knowledge for logistics professionals without OR background.

Several researchers have emphasized the need for research on the situations in which different approaches for decision support are applicable. Murphy (2005a) and Olhager (1995) stress it for OR techniques specifically; Rosenhead and Mingers (2001a) focus on OR in general; Andersen (1999) states it for tools for business process improvement.

In order to achieve the above overall objective, three specific objectives are now introduced and motivated.

1. Identify, classify and characterize the typical OR techniques used to support manufacturing logistics in practice. Identify and classify the manufacturing logistics decision types supported.

A key prerequisite for useful research on OR applicability is that concepts and classifications used are purposeful and clearly defined. The relevance of much of the existing literature on OR applicability is limited because this requirement is not satisfied. For example, surveys on OR use often employ classifications that are not mutually exclusive, and they do not define the different classes. The objective is therefore to develop a well-defined classification of OR techniques that allows rigorous research on their applicability. The classification should also be purposeful, in the sense that it highlights the OR techniques frequently used to support manufacturing logistics. This will constitute enhanced knowledge on the applicability of OR techniques and thus contribute to this thesis' overall objective. Similarly, a well-defined, rigorous classification of decisions benefitting from OR should be developed.

2. Provide empirical evidence of how the applicability of OR techniques depends on different problem situation characteristics.

If an OR technique is appropriate in a given context depends on numerous factors, such as available time and resources, expertise, motivation and the level of technological awareness of the involved companies. There is generally agreement that a key such factor is the nature of the problem situation. As mentioned above, several studies have shown that mismatch between problem situation and OR technique is a frequent reason for failure of OR applications in practice.

Literature linking OR techniques to problem situation characteristics is often made from the biased perspectives of the different techniques' experts, with a focus on 'selling' their technique, rather than providing objective help in selecting suitable techniques. For instance, [discrete-event] simulation is stated to be often the only means for accurately predicting performance if the systems modelled are subject to significant levels of variability (Robinson 2004). Optimization is declared to be the only analytical tool capable of fully evaluating large, numerical databases to identify optimal, or demonstrably good, plans (Shapiro 2001). While these statements can provide some indications of the appropriateness of different techniques, they are often of limited practical support for logistics professionals, who typically face systems that simultaneously require good plans, are data-intensive, and are highly variable.

What is really needed is an understanding of the problem situations in which the different OR techniques' strengths are most valuable.

Findings should be supported by *empirical evidence*, which is one of the essential elements of scientific research (Cooper and Schindler 2003). Claims made by experts on the applicability of OR techniques are often not supported by such evidence. A number of surveys have provided some empirical data, but they often concentrate on just one OR technique or one sub-field of manufacturing logistics, they faced the problems of lacking rigorous classifications addressed above, were based on small samples and date many years back. The second objective is therefore to provide substantial, up-to-date empirical evidence of the type of problem situations that can benefit from the different OR techniques.

3. Develop guidelines that help logistics professionals understand if and how OR techniques can support a given real-world problem situation.

OR practitioners have often considerable experience in selecting suitable OR techniques. Results from this thesis can help them further increase this knowledge. For people without OR background and experience, however, such as many logistics professionals, judging the appropriateness of OR techniques in a given problem situation is difficult. As stated above, one can observe a lot of confusion among them about the different techniques' range of application. They normally heavily depend on OR professionals' recommendations when it comes to judging if OR techniques can provide added value. As a consequence, there is the danger that a logistics professional decides against the use of an OR-based analysis in situations where such an endeavour would have been fruitful. This implies a lost opportunity for savings by the involved company. The OR community, in turn, has not only lost a project, but also failed to obtain the logistics professional's confidence, and it risks being regarded as academic theoreticians.

The importance of communicating what OR does and what it can be used for has been recognized by numerous researchers. Murphy (2005a) states that 'the main unsolved issue is developing ways of communicating and marketing intangible solutions to business problems when most managers do not understand the mathematics involved and other disciplines offer tangible approaches.' Hooker (2007) points out that 'our academic colleagues do not know where to put us, because they honestly do not understand what we do.'

Despite the importance of making people outside the field understand what OR does and in which contexts OR can provide added value, little work has been carried out with this purpose. OR textbooks are concerned with a mathematically rigorous and pedagogical account of OR techniques, at most outlining some of its more general advantages and disadvantages. Logistics textbooks sometimes present the use of OR techniques, but they provide limited guidance on how appropriate they are in different contexts. This thesis' third objective is therefore to explain to people without OR background in which situations OR techniques are likely to be beneficial, and how they work. It thereby follows Murphy's (2005a) request for research 'developing frameworks to explicate where OR works and where other approaches work better to highlight opportunities in OR'.

The same author motivates this thesis' research objectives more generally by stressing that 'we come from the engineering tradition of doing rather than from a research tradition of observation and synthesis. Yes, especially for faculty members of business schools, engaging in observation and synthesis can be a fruitful path of research that would be of value for practitioners and the student who are future customers of OR' (Murphy 2005a).

1.5 Research scope

The scope of this thesis can be defined in terms of

- the organizational functions and decision types
- the approaches and techniques for decision support
- the specific issue of concern

In terms of organizational functions and decisions, the scope is best characterized as logistics in manufacturing companies, in this thesis defined as manufacturing logistics. As explained, logistics is a key activity in manufacturing companies, and it is assumed to be a major source of competitiveness (Alfnes 2005, Christopher 2005, Bowersox et al. 2002). Manufacturing logistics concerns the design, planning and control of material and related information flows in manufacturing companies and their supply chains. It involves a great variety of decisions. The temporal scope of such decisions ranges from daily, short-term decisions all the way to one-of-a-kind, long-term issues. The logistics system scope can concern a single machine or workstation, a manufacturing cell or shop, a plant, an entire company or a supply chain consisting of several independent actors.

In terms of decision support approaches, this thesis concentrates on OR techniques developing and using quantitative models of material/information flows. Hundreds of successful applications of these techniques, described in *Interfaces* and other sources, testify to their potential to support operations and especially logistics. They suggest that OR techniques constitute a particularly promising approach to supporting decision-making in manufacturing logistics. Several surveys, such as Stenfors et al. (2007), have found that production and logistics are among the most important application areas of OR. This further justifies the scope of this thesis.

The use of OR for decision support in real-world organizations is sometimes called the *practice of OR*. It is a broad field with numerous research opportunities. For a recent account, see Murphy (2005a, 2005b, 2005c). This thesis addresses one specific issue within the practice of OR: The *applicability* of its techniques. The applicability of an OR technique in a certain context is the degree to which it can provide useful decision support. This thesis studies the applicability of OR techniques by addressing the question ‘In which circumstances is it appropriate to use them?’ As explained above, this is a key issue because OR techniques can provide a distinct competitive advantage, but only if they are applied in the right contexts. The majority of this thesis focuses on one particular contextual aspect, the problem situation. While this is a key factor affecting the success of OR, it must be remembered that more managerial, relational, educational and behavioural factors also play a role. Such factors include top management involvement, management and communication skill of the involved participants, technical OR skills, motivation etc. They are paid less attention to in the present thesis because they are treated in general terms in other research areas, for example organizational behaviour, marketing and business strategy (Murphy 2005a). When assessing the potential of OR in a given context, the whole range of factors needs of course to be taken into account.

An additional specification related to the scope of OR techniques is that this thesis mainly investigates the applicability of advanced, sophisticated models and techniques, typically developed and implemented by OR professionals. Calculus and simple spreadsheet models

are of course used very frequently for decision support in many organizations (Power and Sharda 2007, Stenfors et al. 2007), but their applicability is addressed only marginally. This is because (1) model applicability is mainly in dispute for more advanced techniques, (2) confusion among logistics professionals concerns predominantly advanced techniques, and (3) using advanced techniques is particularly resource-consuming, so it is particularly important to know in which situations they can provide added value.

1.6 Selecting OR techniques in MOMENT: A motivating case study

Section 1.4 presented and motivated the research objectives of this thesis. In order to illustrate and further emphasize their importance, the present section describes and discusses a real-world case the researcher was part of during his employment at SINTEF. It concerns the selection of OR techniques in the MOMENT project. The project is first briefly introduced, before one particular activity, the selection of OR techniques, is described in detail and followed by a discussion.

1.6.1 The MOMENT project

MOMENT (Mobile Extended Manufacturing Enterprises) was a three-year research project funded by the European Union's research programme 'Competitive and sustainable growth'. Its consortium consisted of academic as well as industrial organizations from several European countries, with SINTEF as the overall project coordinator. A key participant was Raufoss Chassis Technology, a manufacturer of wheel suspensions (Figure 1-2), who delivered its products to several of the world's leading automotive original equipment manufacturers (OEMs). Raufoss Chassis Technology's role in MOMENT was to provide practical insights, specify industrial requirements and test the results developed in MOMENT in order to assure their practical relevance.



Figure 1-2: A wheel suspension produced by Raufoss Chassis Technology

MOMENT emerged as a response to the increased competitive pressure in the automotive industry, with OEMs placing ever-tougher requirements to their suppliers of components and sub-systems. Such suppliers are required to co-develop components for global product platforms and deliver just-in-time, while continuously reducing costs and environmental pollution. European supplier manufacturing companies, such as Raufoss Chassis Technology, therefore had to create efficient operations in the entire supply chain of their products, i.e. in the *Extended Enterprise*. They also had to establish new plants close to the OEMs' plants worldwide, and transfer the Extended Enterprise solutions to these new plants (Figure 1-3).

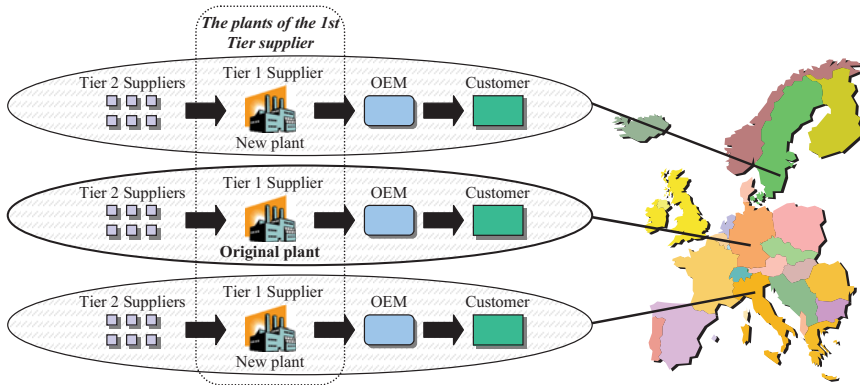


Figure 1-3: Plants and Extended Enterprises of a global automotive supplier

The goal of the MOMENT project was therefore to develop a methodology to support automotive suppliers in rapid establishment and efficient operations of their Extended Enterprises. The methodology had to consist of frameworks, guidelines and software prototypes assisting managers in a variety of decisions related to logistics and supply chain management. Raufoss Chassis Technology was to be the first industrial actor benefitting from the methodology, which was then to be made accessible to a wider industrial arena.

1.6.2 Selecting OR techniques

This section focuses on work package four of the MOMENT project and reports how OR techniques were selected as a part of it. This description is made from the researcher's own, partial and subjective perspective.

The objective of MOMENT's work package four was to develop a strategic decision support system which helped decision-makers take sound decisions when establishing new plants. The decision support system had to address the needs of typical automotive component suppliers, such as Raufoss Chassis Technology, and support the design of Extended Enterprises by addressing logistics-related issues such as plant location or supplier selection. The project proposal planned the use of OR techniques, preferably advanced ones, given recent years' success of such techniques to support tactical/strategic decision-making in logistics and supply chain management. Besides these requirements, system specifications were very open.

In order to ensure the practical relevance of the system to be developed, the project team investigated the needs of industry by means of Raufoss Chassis Technology as a case company. A number of OR professionals with different specializations were then gathered to select OR techniques that could appropriately address these needs. There were people working with optimization as well as people with a background in discrete-event simulation. In the weeks that followed, several meetings were held in order to select suitable OR techniques.

As the researchers sees it, these meetings resulted in misunderstandings and discussions – sometimes even arguments – between the experts in different OR techniques. Some people emphasized the advantages of optimization, which led to arguments with advocates of discrete-event simulation. Others tried to understand how to make optimization work in MOMENT, not paying enough attention to the fact that it might not be an appropriate

technique at all, or that other techniques might work better. The researcher felt that there was not enough focus on an objective assessment of the opportunities and limitations of each technique. Few efforts were made to understand the problem situation and find OR techniques that matched it well.

As a result, these meetings did not really help the project team understand which OR techniques to choose. They neither resulted in a uniform recommendation from the OR community, nor did they provide the project team with the information necessary to decide which technique to go for. The project team was left with quite some confusion.

The need to take a decision eventually led to the selection of optimization. Subsequently, an optimization model of a generic automotive supplier's supply chain was formulated. This model was, however, never implemented in a decision support system and eventually abandoned. Instead, the project team turned to discrete-event simulation because it was also known for modelling logistics flows. Several documents were written that described and specified the functionality of a decision support system based on discrete-event simulation. The intention was to purchase a commercial general-purpose discrete-event simulation software system and to program a user interface customized to the project's needs. However, these plans were not implemented either. Finally, the project team selected a third quantitative modelling technique: 'spreadsheet' simulation. A generic spreadsheet model based on activity-based costing principles was developed that could support cost analysis in the Extended Enterprise. This generic decision support system eventually became one of the project's deliverables.

1.6.3 Discussion

The previous subsection described the way OR techniques were selected in MOMENT. In short, the process involved quite some fumbling and confusion, as well as several attempts to use OR techniques that eventually failed. These incidents show several points:

- The question of choosing OR techniques is an existing, relevant, and difficult issue in practice.
- The way techniques are selected in practice is not always as effective as it could be
- People without OR background, such as the majority of the MOMENT project team, have little means to judge the soundness of OR professionals' recommendations, let alone to assess the appropriateness of different OR techniques themselves.

In the researcher's opinion, the reason for these problems is a lacking understanding of the applicability of OR techniques. In a preliminary literature review, he identified little research that systematically investigated the situations where OR techniques could provide added value. Similarly, few attempts have been made to communicate to people without OR background which situations could benefit from OR techniques. This identification of gaps in research, with its unfortunate effects on practice, led to the issues, problems and objectives of this thesis. They were elaborated in general terms in Sections 1.3 and 1.4.

At the end of the thesis, Section 9.14 returns to the MOMENT case in order to illustrate how the knowledge developed could have made technique selection in MOMENT more effective. The next section presents this thesis' overall structure and content.

1.7 Thesis structure and content

Figure 1-4 shows the overall structure of this thesis. It is organized into five parts, each consisting of two chapters. The content of each will now be briefly presented.

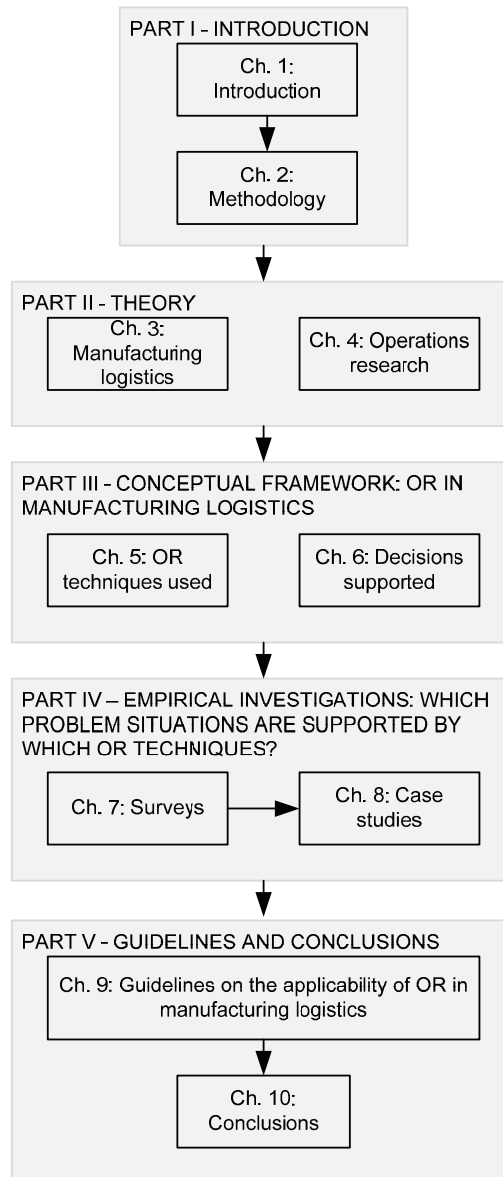


Figure 1-4: This thesis is structured into five parts, each consisting of two chapters.

Part I contains the introduction and the methodology chapter. The introduction sets the stage for this thesis by first broadly introducing the field of study, then quickly narrowing it down to the specific issue of concern, the research problems and gaps as well as its objectives. The

research scope is precisely demarcated in a separate section. The introduction also presents a motivating case study, thesis structure, related publications and a definition of the different groups of professionals distinguished. The methodology chapter first devotes some space to the research setting and how it has affected the what, why and how of this thesis. An overview of the research design and process is then provided. This is a particularly important section because it shortly but comprehensively describes the red line of this thesis. The chapter also contains a discussion of the thesis' main philosophical and methodological choices in the light of relevant concepts and frameworks. It concludes with some lines on how to assess the quality of research.

Part II uses literature to develop the basic notions, concepts and perspectives that lay the foundations of the research carried out in subsequent parts. Chapter 3 reviews the areas of operations management, supply chain management, logistics and manufacturing, before the manufacturing logistics concept is introduced and discussed. It also presents several established frameworks of typical activities/decisions within the scope of manufacturing logistics. Chapter 4 introduces the field of operations research as an approach to support such activities and decisions. The main focus of the chapter is on how quantitative models are used to support decision-making. A brief overview of model types and techniques is also provided. The chapter then discusses the gap between OR theory and practice and elaborates on the applicability of OR techniques in practice. Technique selection is addressed from an operations management perspective and its importance and difficulty illustrated. The chapter concludes with strengths and limitations of OR, as well as a review of literature that aims to characterize the situations that can benefit from OR.

Part III develops a framework for studying and discussing the applicability of OR techniques in manufacturing logistics. Chapter 5 proposes a classification of the typical OR techniques used, consisting of deterministic optimization, discrete-event simulation, queuing theory and inventory theory. The chapter also discusses strengths and weaknesses, makes some general comments on the problem situations in which each technique is useful and compares them along some relevant characteristics. Chapter 6 proposes a classification of manufacturing logistics decisions supported by OR, consisting of seven decision types. Both chapters are structured the same way: First, a set of criteria is established which the classifications should satisfy. Relevant existing literature is then assessed along it. Based on such literature as well as empirical evidence from large surveys of OR applications, classifications are then introduced and assessed against the criteria initially set out. Finally, the two classifications are integrated into a framework which is used in subsequent chapters.

Part IV constitutes this thesis' empirical part. A large number of successful OR applications is studied in order to better understand the link between problem situation characteristics and OR technique applicability. Chapter 7 presents two extensive surveys of OR applications described in the literature. Problem situation characteristics to be investigated in these surveys are identified first, followed by a review of other researchers' surveys. The detailed methodological choices related to the two surveys are then presented and justified. Finally, and most importantly, survey results are presented and many of them also discussed. This allows verifying some literature claims about the applicability of OR, as well as putting forward some new propositions. Survey discussion is continued as a part of Chapter 9. Chapter 8 presents three case studies that provided additional, in-depth knowledge on the situations in which OR techniques can be applied, as well as on how they work. The chapter devotes considerable space to methodological issues, especially the selection of cases. Concise descriptions of each case are then set out, containing relevant information about the

problem situations and the use of OR for decision support. The chapter is finalized with a comparison of the cases to survey findings.

Part V integrates all the knowledge reviewed and developed into a comprehensive overview of the applicability of OR in manufacturing logistics, and it presents some final conclusions. Chapter 9 contains this overview, presented in the form of guidelines for logistics professionals that highlight the situations in which OR techniques can be beneficial. First, the guidelines' purpose is detailed, similar earlier/existing guidelines reviewed and some methodological aspects addressed. Thereafter, their overall structure is shown and instructions on how to use them given. Practice-relevant issues related to the applicability and use of OR techniques are then introduced and motivated. These are the issues focused on in the actual guidelines, which are presented in Sections 9.7 to 9.13. After the actual guidelines, the motivating case study from the introduction chapter is reviewed in order to illustrate their use and usefulness. The chapter concludes with the guidelines' core elements. Chapter 10, finally, rounds this thesis off with some concluding reflections. The research story line is briefly reviewed, the main contributions summarized, thesis quality assessed, significance and limitations discussed and implications for different groups of professionals outlined. Finally, the future of OR in manufacturing logistics is discussed and opportunities for further research highlighted.

1.8 Publications

In the course of this doctorate study, developments and results were regularly described and published at conferences and in books. This has led to the following relevant publications, presented in chronological order:

- Semini, M., H. Fauske, J. O. Strandhagen. 2008. Which manufacturing logistics decisions are supported by operational research? A literature survey. T. Koch, eds. *IFIP International Federation for Information Processing. Volume 257. Lean Business Systems and Beyond*. Springer, Boston, Massachusetts.
- Semini, M., H. Fauske, J. O. Strandhagen. 2006. *Applications of discrete-event simulation to support manufacturing logistics decision-making: A survey*. Proc. 2003 Winter Simulation Conf., Monterey, California.
- Semini, M., H. Fauske, J. O. Strandhagen. 2006. *Simulation methods and educational games: Application areas for learning and strategic decision-making in manufacturing operations*. Proc. 10th International workshop of the IFIP WG5.7 special interest group on experimental interactive learning in industrial management. Trondheim, Norway.
- Semini, M., Fauske, H., Gran, E. 2005. Use of model-driven decision support methods for supply chain design. K. Demeter, ed. *Operations and Global Competitiveness*. Hungarian Association of Logistics Purchasing and Inventory Management, Budapest, Hungary.
- Semini, M. 2004. Verdikjededesign: Et oppsummerende rammeverk. B. Dale, R. Karlsdottir, J.O. Strandhagen, eds. *Bedrifter i nettverk*. Tapir, Trondheim, Norway.

1.9 Groups of professionals distinguished in this thesis

This thesis distinguishes between several groups of professionals. The most important distinction is between logistics professionals and OR professionals. Table 1-1 presents the meaning of these and a number of related terms as they are used in this thesis. Note that the professions are not mutually exclusive, that is, the same person can have several roles. This is even desirable. Nevertheless, it is common that logistics decision-makers have limited knowledge and expertise in OR, and that the OR professionals who develop the decision support models do not have direct logistics decision-making responsibilities.

Table 1-1: Main groups of professionals distinguished in this thesis

Logistics professionals	OR professionals
<p>Logistics professionals have a background in logistics, work with logistics problems and make logistics-related decisions. They are also called <i>problem-owners</i>. They include</p> <ul style="list-style-type: none"> • Logistics decision-makers in manufacturing and service companies • Logistics consultants, i.e. people who work closely with decision-makers and assist them in decision-making • Logistics researchers concerned with theoretical development of logistics concepts and theories <p>Logistics professionals often do not have a background and experience in OR. The purpose of this thesis is to make them more familiar with the applicability of OR techniques.</p>	<p>OR professionals have a background in OR and work with the development and use of OR models. They are also called <i>model-owners</i>, <i>modellers</i>, or <i>analysts</i>. They include</p> <ul style="list-style-type: none"> • OR practitioners, i.e. people who support logistics professionals by developing and using OR models for decision support • OR experts, i.e. experienced OR professionals who have developed into experts in the technique(s) they are good at • Researchers concerned with theoretical development of OR, such as models and solution algorithms <p>For OR professionals, especially those new to the field, this thesis can provide a better understanding of the applicability of OR techniques.</p>

In addition, the following professions are sometimes mentioned:

Software developers/vendors	People who develop model-driven decision support systems, i.e. computer software systems that assist decision-makers by using OR models
Educators	People who teach subjects from the fields of OR or operations management.

Section 10.5 in the concluding chapter describes and exemplifies how the different groups of professionals can use the present thesis.

1.10 Summary

This Introduction chapter has set the stage for this thesis by first broadly introducing the field of study, then quickly narrowing it down to the specific issue of concern: The applicability of OR techniques to support decision-making in manufacturing logistics. There is a lack of research addressing this important issue, which leads to considerable confusion in practice. Based on such research gaps and problems, the overall objective of this thesis was stated: To

increase knowledge on the applicability of OR techniques to support decision-making in manufacturing logistics, and to provide an overview of such knowledge for logistics professionals without OR background. In order to achieve this overall objective, three specific objectives were then defined. They involve the development of classifications and characterizations, the collection and analysis of empirical evidence as well as the development of guidelines. This thesis' precise research scope was then defined in terms of organizational functions and decisions types, decision support approaches and the specific issue of concern. The MOMENT case was presented in order to further motivate thesis objectives by illustrating that the selection of appropriate OR techniques can be challenging. Finally, some space was devoted to thesis structure, publications and a definition of the different groups of professionals referred to in the thesis. A distinction was made between OR professionals and logistics professionals, even though one person can have both roles. The next chapter is dedicated to various contextual, methodological and philosophical issues of relevance for this thesis.

2 Methodology

This chapter collects overall considerations related to research methodology. First, some thoughts are presented about contextual factors that can have affected the what, why and how of this thesis. The second section provides an overview of the research design and process. This is a particularly important section because it shortly but comprehensively describes the red line of this thesis. The chapter then contains a section on important philosophical and methodological choices, based on relevant concepts and frameworks from the literature. It concludes with some lines on how to assess the quality of research.

2.1 Research context

Easterby-Smith et al. (2002) point out that good research ideas are rarely derived directly from literature. Usually, numerous contextual factors shape the what, why and how of research, such as the researcher's background and experience, academic and corporate stakeholders, trends in the field of study etc. Often, the literature-based justification and anchoring only takes place *post hoc* (Easterby-Smith et al. 2002). The present research has been no exception, and this section therefore discusses some crucial contextual factors within which it has been carried out.

Background and experience

Most importantly, the research issues and objectives have been influenced by the researcher's background in mathematics and his experience from working in logistics improvement projects.

After graduating in pure mathematics at the University of Lausanne in Switzerland in 2001, the researcher felt the need to apply his analytical capabilities in practical contexts. The research unit in operations management based at SINTEF and NTNU in Trondheim, where he has been working since 2002, provided an excellent arena for this because the researcher was able to combine the acquisition of theoretical knowledge in relevant fields with practical application in real-world contexts. The research unit is affiliated to the following organizational units at SINTEF and NTNU:

- *SINTEF Technology and Society*, a multi-disciplinary research institute that carries out applied research in the fields of technology management, transport and health care. The institute aims at process improvement and increased competitiveness in industry and the public sector, with a healthy balance between development of solutions for practice and advances in theoretical development. One of its core strengths is a holistic understanding of society, technology, organization and economics. (www.sintef.no)
- *NTNU's Department of production and quality engineering*, which works on the point of intersection between technology and management, with issues tied to operations, industrialization and production, along with quality and safety. The department carries out research by means of PhD programmes and project-based applied research, often in collaboration with SINTEF. Numerous courses at Master and PhD level are offered as well. (www.ntnu.edu/ipk)

The research unit in operations management is strongly influenced by these two organizations. It has a long tradition in improving logistics and supply chain management in Norwegian manufacturing enterprises, which was decisive for the researcher's focus on manufacturing operations in this thesis. It allowed the researcher experience industrially-

based research and development, which explains the applied perspective he has in his research.

With a background in mathematics, it seemed natural to him to support the logistics improvement projects with quantitative models. With such models, he hoped to increase the understanding of the real-world systems considered, to predict the effects of various changes, and – not least – to provide a more objective, rational basis for decision-making than qualitative reasoning and justification. However, the use of quantitative models in practice turned out to be more difficult than first expected. For various reasons, for example limited time and difficulty to quantify key factors and relationships - this approach did not work as often as it first seemed. Similarly, he experienced that the models developed by professionals did not always result in practically relevant results. The MOMENT case, presented in Section 1.6 and reviewed in Section 9.14, describes these difficulties in detail for a specific project the researcher was part of as a SINTEF employee. These observations and experiences led to considerable confusion and frustration for the researcher, and they eventually resulted in this thesis' research issue and objectives.

Fields of study, disciplinary trends and religions

Easterby-Smith et al. (2002) explain that research issues, objectives and methods are often considerably influenced by current trends, fads and fashion in the academic discipline. For example, in the early 2000's, some of the hottest areas in academic management research included knowledge management/creation, globalization and e-commerce (Easterby-Smith et al. 2002). By selecting a popular issue, one is assured a lot of interest from other researchers and even practitioners, useful discussions and feedback, opportunities to publish in special issues in journals, and more generally a positive attitude towards ones research. One drawback is that the trends can change, which would leave the researcher with findings of limited interest.

The present research is interdisciplinary and lies at the interface between operations management, which aims to make operations more effective, and operations research, which concentrates on developing and analyzing quantitative models. The researcher does not see how trends in these disciplines would have influenced his research issue and objectives. On the contrary, he felt that neither of the disciplines pays substantial attention to them. Murphy (2005c) remarks this for operations research, but emphasizes that it is due to the specialized skills and interests of OR professionals more than the subject's lacking research potential. In the operations management discipline, the subject may often be avoided because it requires familiarity with quantitative modelling techniques. The researcher often felt that he had fallen between different research strands or 'religions'. He wanted to forward the use of quantitative techniques in operations management, but only when it was beneficial for practice. Similarly, he did not advocate any particular OR technique, but aimed to objectively find the most promising one(s) in a given context. With hindsight, he may have avoided some of the problems encountered during his study by staying firmly within one research discipline and choosing a more mainstream topic.

2.2 Research design and process

According to Yin (2003), the research design is the logic that links the data to be collected to the initial research questions. To put it simply: **In order to achieve the research objectives (increasing knowledge on OR applicability), the researcher studied a large number of successful OR applications, used them to assess the problem situations in which OR techniques were useful and how they worked, and developed guidelines based on this.** The present section explains this in more detail by describing the research process, the ‘red line’, of this doctorate study.

A process is typically defined as a logic series of activities that transform input to output or results (Andersen 1999). According to Gill and Johnson (1991), however, ‘... the research process is not a clear-cut sequence of procedures following a neat pattern but a messy interaction between the conceptual and the empirical world, deduction and induction occurring at the same time’. While the term ‘research process’ thus may be considered as contradicting actual practice, it emphasizes that, despite the iterative nature of many projects, it is important to have an appreciation of the sequencing of the main elements of a research project.

Figure 2-1 shows a sequential process model of this doctorate research. It must be emphasized that this picture is a gross simplification of the actual research process, which was – fully in line with Gill and Johnson’s (1991) observation – a messy, iterative back-and-forth between the different activities and outcomes. The purpose of the figure is to allow the readers to get an understanding of the key elements of this research.

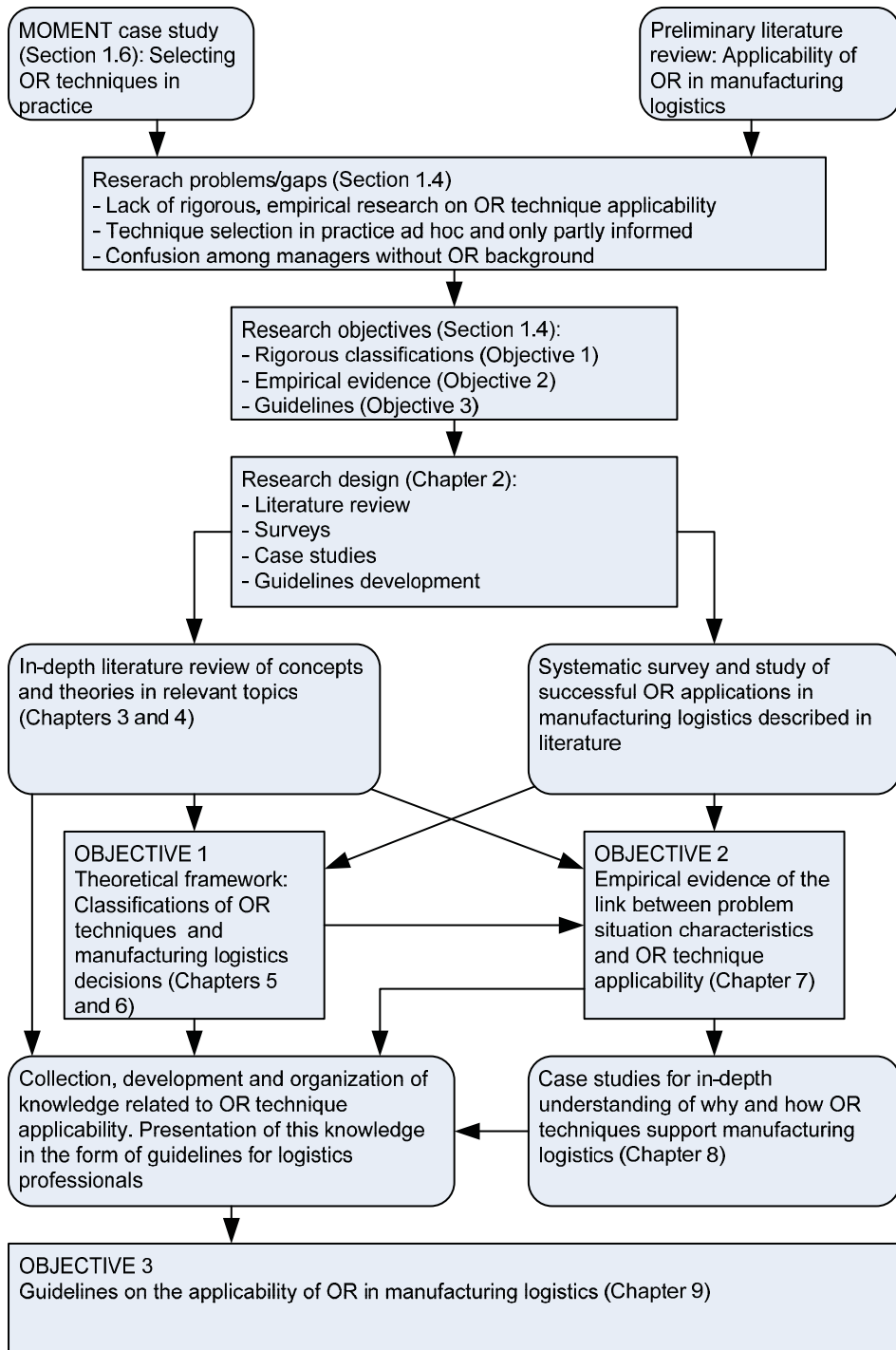


Figure 2-1: The main activities (rounded rectangles) and main outcomes/results (rectangles) in this thesis’ research process. The arrows signify ‘provided input for’.

The present research emerged from a number of professional experiences by the researcher related to the practical application of OR techniques. They are illustrated by the Moment case study in Section 1.6. A subsequent review of the literature led to the identification of several research gaps, namely the lack of theoretical knowledge on the applicability of OR techniques to support manufacturing logistics in practice, manifested in practice by fumbling technique selection processes as well as emotionally-loaded discussions and confusion. Based on these gaps, research objectives were established that sought to mitigate them (Section 1.4). Essentially, the goal was to develop objective knowledge on the situations in which OR techniques could be useful, and to develop guidelines for the selection of techniques that could be understood by non-OR-experts, such as many operations and logistics managers.

How could such an objective be achieved by a young researcher without much experience in applying OR techniques? It seemed appropriate to study successfully completed OR applications, ideally a large number, and learn from them (as suggested by Littlechild and Shutler 1991). This way, the researcher could speed up the acquisition of experience, the knowledge developed could be empirically supported, and the danger of being biased towards certain techniques was reduced. The research literature contains hundreds of descriptions of such OR applications, many of them published in the journal *Interfaces*, which is entirely dedicated to OR practice. A survey of papers from this journal was therefore considered to be a good overall research strategy, more appropriate than, say, carrying out a questionnaire-based survey of companies or OR practitioners. The sample of OR applications was augmented by a second survey, using papers published in *Winter Simulation Conference* proceedings. These basic methodological choices are further detailed and justified in Section 7.3. They resulted in a sample of nearly 200 OR applications.

In parallel, a comprehensive literature review of relevant concepts and theories was carried out, which led to an overview of manufacturing logistics and operations research (Chapters 3 and 4), as well as the identification of specific weaknesses in existing literature on the applicability of OR techniques. As a first step towards the overall thesis goal, a rigorous classification of OR techniques used in manufacturing logistics was developed, including a characterization of each technique (Chapter 5). Similarly, a classification of the typical decisions supported was created (Chapter 6). These classifications were developed based on existing theory and the 200 OR applications studied. A theoretical framework for the present study was thereby established.

Literature was then used to identify a number of problem situation characteristics that seemed to affect the applicability of OR techniques, such as the planning horizon. The sample of OR applications was used to assess the link between these characteristics and OR usage. This work is presented and discussed in Chapter 7. It provided empirical evidence that allowed testing numerous claims as well as developing some new propositions.

Quite some knowledge had been gathered at this stage, but greater insights into why and how OR techniques were used was needed before guidelines could be developed. The sample of 200 OR applications was again useful, but a number of case studies were also carried out addressing these 'why' and 'how' questions. The detailed case strategy employed is treated in Section 8.1. The literature was also further scrutinized. Finally, the entire body of knowledge from literature, surveys and case studies was organized and integrated into comprehensive managerial guidelines covering a wide spectre of OR techniques and manufacturing logistics decisions (Chapter 9). Some methodological issues related to the building these guidelines are presented in Section 9.3. In particular, it should be emphasized that the empirical basis for the

guidelines is much wider than the two surveys the researcher carried out himself, including also evidence from several surveys carried out by other researchers.

Figure 2-2 illustrates the link between research activities and outcomes, with emphasis on the fact that most outcomes rely on several activities. As can be seen, for example, existing literature provided knowledge for most outcomes.

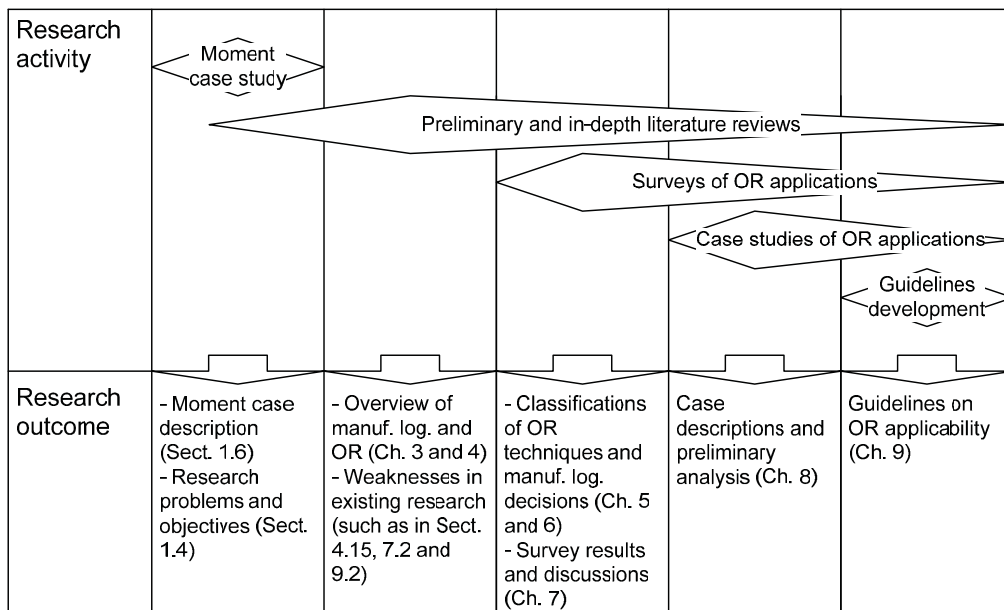


Figure 2-2: The link between this thesis' research activities and outcomes

2.3 Philosophical and methodological foundations

Research designs are about organizing research activity, including the collection of data, in ways that are most likely to achieve the research objectives; they involve numerous choices, many of which are closely related to different philosophical positions (Easterby-Smith et al. 2002). In this section, some key philosophical and methodological choices of this thesis are therefore discussed. The following four elements are covered:

- The types of knowledge and theories developed
- The paradigmatic choice
- The strategies of enquiry employed
- The detailed methods for data collection and analysis

The first point discusses knowledge and theory in very general terms. The remaining three are typical elements characterizing a research design, as suggested by Creswell (2003).

This section is the result of reviewing literature on research philosophy and methodology, and applying it to the present research. In general, the researcher has made the following observations about the literature:

- Terms and concepts, such as positivism or empiricism, are used in a number of different ways in the literature.
- Each of these terms is usually related to not just one idea, but a collection of concepts and elements.

These observations may explain some of the confusion among researchers. They imply that it will not usually be possible to ‘pigeonhole’ a piece of research within one or a few of these concepts. Typically, it will be more appropriate to use expressions such as ‘contains elements of ...’ or ‘has a tendency towards...’ etc. This should be kept in mind when reading the present section.

2.3.1 Types of knowledge and theories developed

The role of research can be defined as the creation and development of new knowledge (Karlsson 2009). In order to carry out good research, the researcher therefore needs to understand what knowledge is and how it can be created/developed. In this subsection, some general definitions of knowledge and theory are reviewed and used to characterize the present research.

The concept of knowledge has been discussed for centuries. The classical Greek philosophers Socrates, Plato and Aristotle distinguish it from skill and attitude; knowledge is built on rational formula, skill is the practical know-how, and attitude is the values of an individual (Karlsson 2009). There is today no single agreed definition of knowledge, nor any prospect of one, and there remain numerous competing theories (www.wikipedia.org). For example, Turban (1992) defines it as ‘information that has been organized and analyzed to make it understandable and applicable to problem solving and decision making’. This definition is made within the context of expert systems and artificial intelligence, and it well characterizes the knowledge developed in Chapter 9, the guidelines on OR applicability in manufacturing logistics. Another aspect of knowledge relevant with respect to these guidelines is the distinction between tacit and explicit knowledge. According to Karlsson (2009), one can to some extent say that theoretical development in research is about explicit knowledge while the practice involves considerable tacit knowledge. This underpins the guidelines as a contribution to theoretical development, since their purpose is precisely to make tacit knowledge explicit.

There are, however, also much wider definitions of knowledge, such as: ‘Knowledge consists of truths and beliefs, perspectives and concepts, judgement and expectations, methodologies and know-how’ (Wiig 1993). This perspective provides a better characterization of the remaining knowledge developed in this thesis. The classifications developed in Chapters 5 and 6 contribute to the clarification of concepts; the findings and implications discussed as a part of the surveys (Chapter 7) can be considered as contributing to truths by supporting or rejecting various claims on OR applicability.

Related to the concept of knowledge is that of theory. Again, there is no one commonly agreed-upon definition of theory. A frequently cited work is the one by Wacker (1998), for example cited by Voss (2009), who considers theory as being made up of the following four components (Wacker 1998):

- definitions of terms or variables
- a domain (the exact setting in which the theory can be applied)
- a set of relationships
- specific predictions

Arlbjørn and Halldorsson (2002) distinguish between solid and loose theory. Solid theory refers to established theories such as resource-based theory, transaction cost theory and network theory. Research based on solid theories employs the strict well-known language from the theory considered. In loose theory, the language is more loose-coupled using words that may be open to different interpretations. Typically, loose theory is made up of propositions or hypotheses describing or explaining certain aspects of the real world. (Cox 1996) termed this type of theory ‘barefoot empiricism’.

The present thesis develops and tests loose theory. As explained in Section 1.4, research on OR applicability, and on OR practice more generally, has been limited. This has been recognized by Murphy (2005a, 2005b, 2005c), who proposes some elements of a theory of the practice of OR. Existing theory on OR applicability can therefore most adequately be seen as loose: A collection of loose-coupled, more or less formalized claims and propositions about when and how OR techniques can provide useful decision support. The present research investigates such propositions and develops new ones by means of various strategies, such as surveys and case studies. It is the typical way of doing research based on loose theory.

The present thesis contributes to all of the four components in Wacker’s (1998) definition of a theory. The classifications of OR techniques and decisions fall under ‘definition of terms and variables’. The survey results are used to support and reject various relationships and predictions about the link between problem situations and OR applicability. The guidelines, finally, sew together numerous elements and propositions into comprehensive theory consisting of all the four components, thereby contributing to a theory of the practice of OR in manufacturing logistics.

2.3.2 Philosophical assumptions

This subsection builds upon the previous and discusses a number of schools of thought about the nature of knowledge and how it can be acquired. They are concerned with issues related to what knowledge is (ontology), how we know it (epistemology), what values go into it (axiology), how we write about it (rhetoric) and the processes for studying it (methodology) (Creswell 2003).

Literature

The different schools of thought are often characterized by different *paradigms*, a concept used in the influential works by Kuhn (1970) and Burrell and Morgan (1979). Such paradigms are often considered as mutually exclusive and based on contradictory assumptions (Mingers 2001a), providing fundamentally different ‘world views’. Various writers present paradigms

and compare them to each other. Creswell (2003) distinguishes between postpositivism, social constructivism, advocacy/participatory knowledge claims and pragmatism. Meredith et al. (1989) oppose the rational to the existential paradigm, and Easterby-Smith et al. (2002) distinguish between positivism and social constructionism. Such texts seem to suggest two main opposing ways of thinking, the one associated with positivism and related views (postpositivism, rationalism, empirical science), the other referred to as social constructivism (and related views such as interpretivism and existentialism).

Positivism is associated with the traditional way of doing research following the 'scientific method' (Creswell 2003), which starts with hypotheses, collects empirical data and uses statistical analysis to falsify or support the original hypotheses (see for example Cooper and Schindler 2003). The world is considered as external to and independent from the researcher and her beliefs, consisting of an objective reality and truth, which the researcher strives to discover. Focus is therefore on empirical observation of observable facts, derived from valid, reliable measurement, and providing results and conclusions which are replicable (verifiable) and generalizable (Bryman 1988). 'Being objective is an essential aspect of competent inquiry, and for this reason researchers must examine methods and conclusions for bias. For example, standards of validity and reliability are important...' (Creswell 2003, Phillips and Burbules 2000). For the positivist, the world is governed by laws that determine how different entities are related to each other (cause – effect). Research therefore aims to examine cause-effect relationships, for example by means of experiments. In order to do this, the scope is reduced to a small number of items (reductionism), expressed by a limited number of variables, often only two, for which cause-effect hypotheses are tested. Even though the positivist stance is usually associated with such a deductive, theory-testing research approach, it is important to realize that knowledge is arrived at through the gathering of facts that provide the basis for laws (inductivism; theory development) (Bryman 2008).

For social constructivists, on the other hand, truth and reality depend on the individual. All observation and analysis depends on the researcher's personal, social and historical context (Creswell 2003). Similarly, the individuals, their actions and the phenomena studied by the researchers are dictated by the specific circumstances found in the situation (Croom 2009). So, as opposed to positivism, there is no objective truth out there, and there are no laws that govern the behaviour in the world. Observing facts with valid and reliable measurement is not possible since what is observed and how it is analyzed, will always depend on the researcher. Similarly, the context-dependent interpretations and behaviour of individuals make generalizations impossible and results dependent on the individuals participating in the research. As a consequence, constructivist research is more concerned with understanding, making sense of, and interpreting the phenomena studied. For example, constructivist research investigating the motives of murderers would focus on understanding why the individuals committed a murder, rather than looking for law-like causes and effects that would explain the murders. Results will depend both on the murderer and the researcher. Thus, constructivist research is driven by meanings. 'These meanings are varied and multiple, leading the researcher to look for the complexity of views rather than narrowing meanings into a few categories or ideas' (Creswell 2003). The process of social constructivism is largely inductive (theory generation), with the inquirer generating meaning from the data collected in the field (Crotty 1998).

A third paradigm is briefly discussed now because it closely characterizes the stance taken in the present research: Pragmatism. In pragmatism, there is a concern with applications – 'what works' – and solutions to problems (Patton 1990). The starting point and focus is the problem,

the research question to be studied, the research objective to be achieved. Research approaches are chosen so as to best develop new knowledge about the problem, even if they belong to different paradigms. So the researchers are 'free' to choose the methods and procedures that best meet their needs and purposes (Creswell 2003). For pragmatists, positivism and social constructivism are not incompatible (Teddlie and Tashakkori 2003), but can provide complementing views and insights on the research problem. At the applied level, strategies of enquiry and methods for data collection and analysis (see below) associated with both paradigms are employed. Such a mixed methods approach is typical for the philosophical stance of pragmatism.

The above paradigms only provide a very superficial and grossly simplified appreciation of three different ways of viewing the world and knowledge. A more detailed treatment should for example distinguish between different ontologies and epistemologies, as well as between science and social science (see for example Easterby-Smith et al. 2002). Such distinctions will allow understanding and positioning of the numerous terms and concepts that have emerged from the philosophical debates. The term realism, for example, denotes a variety of related ontologies in science. The traditional view of realism is that the world is concrete and external, and that laws once discovered are absolute and independent of further observation (Easterby-Smith et al. 2002). The positivist paradigm typically adopts such a realist ontology.

Positioning this research

The present research studies properties of manufacturing systems, especially with respect to material and information flows. Manufacturing systems are viewed as consisting of concrete, physical entities embedded in an objective world external to the observer. Performance is measured by means of quantitative concepts such as cost, time, amounts (for example inventory) and capacities. These systems are assumed to have existence independent of the researcher or the participants' opinions. It is recognized that human factors affect the behaviour of the system (so it does not behave purely like a machine), but it is still considered as possible to discover general rules and cause-effect-like relationships about how the systems tend to behave. In particular, it is assumed that such rules and tendencies can be discovered about the relationship between manufacturing system characteristics and the usefulness of OR techniques to support decision-making.

Relating these considerations to the literature review above, the researcher's ontology is predominantly a realist one, which assumes that there is a reality separate from our description of it (Bryman 2008). In terms of paradigms, the researcher tends towards the positivist end of the scale. Focus is on empirical observation of objective facts, and the goal is to discover cause-effect relationships. However, the research design does not strictly follow the traditional positivist hypothetic-deductive approach (the 'scientific method'). It contains several inductive steps which have been carried out by means of research strategies usually associated with the constructivist paradigm (see next subsection). This was a consequence of the research problems and objectives, which address an issue with little existing theory. The research strategies were chosen such as to best fit the given purpose, which resulted in a mix of more qualitative and more quantitative research. Such an approach is typically associated with the pragmatic paradigm. Thus, the present research relies on several key aspects of the pragmatic paradigm, but it is clearly influenced by positivist thinking as well.

2.3.3 Strategies of enquiry

The strategies of inquiry provide specific directions for procedures in a research design (Creswell 2003). This subsection provides a brief overview of established strategies, with focus on those most closely corresponding to the strategies employed in this thesis.

Literature

Different strategies of enquiry are associated with the different paradigm (Creswell 2003). Frequently used strategies invoking the positivist view are surveys and experiments. Strategies often more associated with social constructivism include ethnographies, grounded theory, case studies and phenomenological research. When knowledge claims are based on pragmatic grounds, strategies are mixed (triangulation). The idea is to employ several strategies in order to mitigate the limitations of any single strategy. Since different strategies provide different types of results, the research problem can be more comprehensively addressed this way. Creswell (2003) describes three procedures to combine different strategies, the sequential, the concurrent and the transformative.

A number of established research strategies are now briefly defined based on literature. The selection is made based on strategies that most closely match the approaches used in the present research:

- *Surveys*: A survey provides a quantitative or numeric description of trends, attitudes or opinions of a population by studying a sample of that population (Creswell 2003).
- *Case studies*: A case study may be understood as the intensive study of a single case where the purpose of that study is – at least in part – to shed light on a larger class of cases (Gerring 2007).
- *Grounded theory*: The researcher attempts to derive a general, abstract theory of a process, action or interaction grounded in the views of participants in a study. This happens in multiple stages of collecting data and refining the categories and interrelationships constituting the emerging theory (Strauss and Corbin 1990).
- *Action research*: Coughlan and Coughlan (2009) refer to Rapoport (1970) for a well-recognized definition of action research: ‘... aims to contribute both to the practical concerns of people in an immediate problematic situation and to the goals of science by joint collaboration with a mutually acceptable ethical framework.’
- *Sequential procedures in mixing strategies*: The researcher seeks to elaborate on or expand the findings of one method with another method. For example, a quantitative method may be used to test concepts and theories first, before a qualitative method is employed for more detailed exploration with a few cases (Creswell 2003).

Positioning this research

As explained above, the researcher has chosen research strategies that best fit the objectives to be achieved, thereby invoking the pragmatist paradigm (with a realist ontology). At the overall level, the strategy of inquiry has been a sequential procedure, mainly by means of surveys followed by case studies. Such mixed method research has been encouraged by many researchers, such as Mingers and Brocklesby (1997), particularly in terms of developing

valuable theory from observation and empirical analysis (Croom 2009). A design driven by case studies following surveys has also been proposed by Yin (2003).

The first objective of this thesis, development of classifications and characterisations, has been achieved by means of inductive reasoning based on existing theory and information on OR applications in manufacturing logistics. Literature contains hundreds of descriptions of such applications, and provided as such a rich data set (see Section 7.3 for details). This approach contained elements of grounded theory, in as much as it was based on an iterative process between data collection and refining emerging categories.

For the second objective, empirical evidence on how OR technique applicability depends on problem situation characteristics, an approach closer to the traditional scientific method was endeavoured. The same sample of OR applications was used as for the first objective, but in a more reductionist way: From each application, information on specific 'survey questions' was collected (OR technique used, decision type supported, planning horizon, system scope, company size and industry). This strategy of enquiry is therefore called a survey, even though it was not of the typical questionnaire-based type.

For third objective, finally, existing theory and results from the first and second objective provided crucial input. Additional in-depth information was obtained by means of a multiple case study. The data collection process of one of these case studies, the Mustad case, contained some elements of action research, in as much as the researcher was himself involved in the OR application studied.

2.3.4 Methods for data collection and analysis

The last element shaping the research design is the detailed methods used for collecting and analyzing data.

Literature

Such methods differ from paradigm to paradigm by how predetermined they are, how close-ended/open-ended the questioning is, and if focus is on numbers or text (Creswell 2003). Typically, in more positivist research, the methods are clearly specified and the questions precisely defined before data collection starts. Predominantly quantitative data is collected and analyzed statistically. In more constructivist approaches, the type of information to be collected often only emerges as data collection takes place. Interviews are typically more unstructured, allowing the individual to talk freely about a particular issue. Data is often collected and analyzed in the form of text.

Positioning this thesis

As explained several times before, a key data source was literature describing OR applications. This source was deemed appropriate because literature contains numerous such descriptions of successful OR applications, and these descriptions normally contain the type of information needed to achieve the research objectives. Thus, it was possible to rely heavily on secondary literature. Nevertheless, for deeper insight, case study data was also collected. This was done by means of semi-structured interviews, written documents and direct participation.

Data collection and analysis involved both numbers and text. For classification development, textual data was used. Survey data was analyzed mainly by studying frequencies (numbers)

and supporting or rejecting various propositions. Some new propositions were also put forward and discussed. The methods for data collection and analysis in the case studies were again mainly text-based. Further details about data collection and analysis are provided in Sections 7.3, 8.1 and 9.3.

2.3.5 Summary

This Section has reviewed methodological ideas and concepts in order to characterize the research design employed in the present research. Its main features are summarized in Table 2-1. Since the research design is the logic that links the data to be collected to the initial research questions (Yin 2003), it is structured according to research objectives.

Table 2-1: A characterization of the present research design in terms of methodological ideas and concepts

Objective	Main methodological features	Type of knowledge developed
Overall objective: Develop knowledge on OR applicability	Realist ontology, pragmatist paradigm with positivist tendency; mixed method approach, sequential procedure (surveys followed by case studies)	Loose theory
Specific objective 1: Classification development	Theory development, inductive; qualitative; method of enquiry: elements of grounded theory based on existing theory and secondary data	Concepts (classifications)
Specific objective 2: Empirical evidence of OR applicability	Mainly theory testing, deductive; quantitative; method of enquiry: surveys; data analysis based on frequencies	Truths
Specific objective 3: Guidelines on OR applicability	Theory development, Inductive; qualitative; method of enquiry: case studies and elements of action research; data analysis mainly in the form of knowledge engineering	Making tacit knowledge explicit

2.4 How to assess the quality of this research?

In reviewing the literature on research quality, the researcher had to realize that there does not seem to be a standard way of assessing the quality of a piece of research like the present thesis. In quantitative social science, typically using surveys or experiments, the notions of validity and reliability provide some standard criteria:

- Validity refers to the extent to which a test measures what we actually wish to measure (Cooper and Schindler 2003). In terms of a question: How closely do the findings correspond to reality?
- Reliability has to do with the accuracy and precision of a measurement procedure (Cooper and Schindler 2003). In terms of a question: If the research was repeated, would the findings be the same?

In a quantitative research context, many procedures have been devised for assessing different facets of these two criteria (Easterby-Smith et al. 2002). Within a more constructivist frame, typically implemented by means of qualitative research strategies, such criteria lose some of their relevance since it is not assumed that there is one absolute truth and objective world that the research aims to discover. For quality assessment of more qualitative research, other

concepts have been proposed, such as credibility, transferability, dependability and confirmability (Hammersley 1992, Guba and Lincoln 1981), as well as overall significance, relevance, impact and utility (Morse et al. 2002). Nevertheless, the importance of transferring the validity and reliability concepts to constructivist research has also been emphasized by some authors as a way to convince examiners that its results should be taken seriously (Easterby-Smith et al. 2002).

Easterby-Smith et al. (2002) discuss evaluation criteria that apply for doctoral theses in management research, which is as such particularly relevant for the present work. They focus on two elements:

- Synthesis of theory and data by presenting some kind of critical reflection, as opposed to simply describing others' work or accounting data gathered.
- Critical evaluation of relevant work and demonstration of some kind of original contribution to the field, in the form of
 - New knowledge about the world of management (substantive contribution)
 - New theories and ideas (theoretical contribution)
 - New methods of investigation (methodological contribution)

These authors emphasize that the contributions have to be clearly stated in the conclusions, and that there should be linkages back to the early parts of the thesis, where existing theories and methods were reviewed and evaluated.

A second source of particular relevance is the good practices in researching operations management proposed by Karlsson (2009). By looking at publications with high impact, this author identified the following patterns:

- Research results must offer a contribution to existing knowledge
- The problem/issue together with earlier/existing knowledge must be made clear
- The approach and rigour in execution must be demonstrated
- Newness is important to get impact
- The language should preferably be easily accessible

This brief review shows that various quality criteria have been proposed for different types of research. Based on it, the researcher proposes to assess this thesis' quality by means of the following criteria:

- Clear statement of problems, issues and earlier/existing knowledge
- Synthesis of theory and data by critical reflection
- Clear statement of original contribution to existing knowledge
- Validity and reliability
- Newness

- Easily accessible language

Section 10.3 in the conclusions uses these criteria to briefly evaluate the quality of the present thesis.

2.5 Summary

This chapter has been devoted to methodological aspects of this thesis. First, it was explained how the researcher's background in mathematics and experience in applied research affected research issue, objectives and methodology. This thesis' red line was then outlined and illustrated. Essentially, the researcher used descriptions of OR applications and a number of case studies to acquire new knowledge on OR applicability and combined it with existing theory into comprehensive guidelines for logistics professionals. As far as methodological choices are concerned, the researcher has a predominantly realist ontology and his paradigmatic stance may be best characterized as pragmatic with a positivist tendency. The strategies of enquiry employed contain elements of surveys, case studies, grounded theory and action research. Data collection and analysis was mainly qualitative, but contained some quantitative elements as well. The chapter concluded with a set of quality criteria that will be used to assess the present thesis.

PART II - THEORY

This part uses literature to develop the basic notions, concepts and perspectives that lay the foundations of the research carried out in subsequent parts. Chapter 3 is devoted to this thesis' scope in terms of organizational activities/decisions, manufacturing logistics. Chapter 4 concentrates on an important group of techniques that can support these activities/decisions: Operations research.

3 Manufacturing logistics

The purpose of this chapter is to introduce manufacturing logistics. The areas of operations management, supply chain management, logistics and manufacturing are first briefly reviewed as manufacturing logistics is concerned with key issues from these areas. Manufacturing logistics is then defined and previous use of the term discussed. Finally, a number of relevant frameworks for classifying manufacturing logistics activities are reviewed.

3.1 Operations management

This thesis is takes the perspective of the area of operations management. This area is therefore introduced here. The area of supply chain management is introduced as a part of it, because of the importance it has gained in recent years.

According to Slack (2007), there are three core functions in any organization: Marketing (including sales), product/service development and operations (see Figure 3-2 below). *Marketing/sales* is responsible for communicating the organization's products and service to its markets in order to generate customer requests. *Product/service development* is responsible for creating new and modified products and services in order to generate future customer requests. *Operations* is responsible for fulfilling customer requests throughout the production and delivery of products and services. It is a function or system that transforms inputs into outputs of greater value (Russell and Taylor III 2003). In addition to the core functions, there are support functions which enable the core functions to operate effectively, among others finance/accounting and human resources.

Operations management is concerned with managing operations. Slack (2007) defines it as 'the activities, decisions and responsibilities of managing the production and delivery of products and service'. Hanna and Newman (2001) define it as 'the administration of processes that transform inputs of labour, capital, and materials into output bundles of products and services that are valued by customers'. Russel and Taylor III's (2003) definition simply is 'the design and operation of productive systems – systems for getting work done'.

Hanna and Newman's (2001) definition refers to the *input-transformation-output* process, which is at the heart of operations. In general, a process can be defined as a logic series of related transactions that converts input to results or output (Andersen 1999). The input-transformation-output process in operations is well illustrated by the *transformation process model*. Figure 3-1 shows Russell and Taylor III's (2003) version of it. Inputs such as material, machines, labour, management and capital are transformed into outputs in the form of products or services. A control system provides feedback backwards in the process, allowing adjustment and improvement of the transformation process and its inputs. A second important backwards flow of information is the requirements for the output, which determine the type and quantity of input fed into the transformation process. The goal of operations

management is to carry out this process efficiently and that the output is of greater value to the customer than the sum of its inputs (Meredith and Shafer 2002).

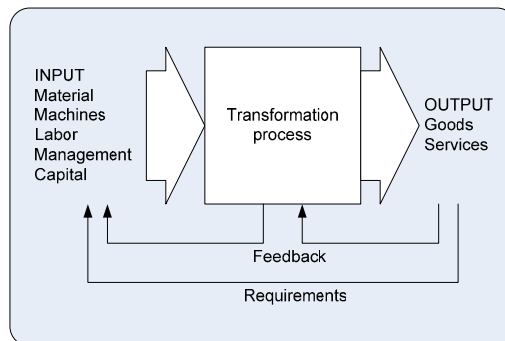


Figure 3-1: The transformation process model (Russell and Taylor III 2003)

Operations and operations management can be found in most businesses. In different sectors, the transformation process takes different forms. In *manufacturing operations*, physical goods are produced. Examples include aluminium, cars, chairs, food and clothes. This thesis concentrates on manufacturing operations, so they will be treated in more detail (Section 3.3). *Service operations* are economic activities that produce a place, time, form or psychological utility for the consumer (Markland et al. 1995). A transportation firm, for example, carries out a locational transformation process, producing a place utility. A hospital produces a physiological value, a cinema a psychological value, a telephone company an informational value etc. A key characteristic of service organizations is the interaction with the customer, which may be highly personal, or a more impersonal one between the customer and the service organization's equipment (Markland et al. 1995).

Traditionally, operations management tended to be restricted to internal operations. More recently, however, organizations have started to realize the importance of thinking and managing in terms of processes rather than functions. Processes typically span across functional and even organizational boundaries. With such an understanding, the scope of operations management has been extended to business areas such as sourcing, transportation, distribution, product design/development, information system activities and marketing.

As organizations started to broaden their view across functional and organizational boundaries, the concept of a *supply chain* gained increasing importance. While there is no universal definition of the term supply chain, it commonly refers to the network of plants and warehouses that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer (adapted from Christopher 2005). A typical supply chain includes suppliers, manufacturers, warehouses and distribution centres and customers. At the different plants in a supply chain, raw materials are processed into intermediate and finished product, which are stored and finally shipped to the final customers (end-users). Information is also exchanged between the different actors, often in the opposite direction of the material flow (e.g. orders). The supply chain is also referred to as the *logistics network* (Simchi-Levi et al. 2008).

The management of supply chains is commonly referred to as *supply chain management* (Croom et al. 2000). Simchi-Levi et al. (2008) define supply chain management as ‘a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses and stores, so that merchandise is produced and distributed in the right quantities, to the right locations and at the right time, in order to minimize systemwide costs while satisfying service level requirements’. Lambert and Cooper (2000) provide a definition developed by the Global Supply Chain Forum: ‘Supply chain management is the integration of key business processes from end user through original suppliers that provide products, services and information that add value for customers and other stakeholders.’ They explain that supply chain management is about integrating key business processes across the supply chain. This focus on integration is reflected in both the above definitions of supply chain management. There are numerous business processes that benefit from integration and are addressed by supply chain management, such as customer relationship management, demand management, product development and order fulfilment.

Today, many companies are aware that effective supply chain management can increase customer service and reduce costs. A flagship example of a company who gained a major competitive advantage through effective supply chain management is Dell. Dell bypassed distributors and retailers, centralized manufacturing and inventories in a few locations, and postponed final assembly until orders arrived. Moreover, Dell’s supply chain involved sophisticated information exchange. The company attributed a significant part of its success to the way it managed flows within its supply chain (Chopra and Meindl 2007). According to Chopra and Meindl (2007), it is today generally agreed that supply chain management plays a significant role in the success and failure of a firm.

3.2 Logistics

One of the core activities within operations and supply chain management is logistics. The area of logistics is now reviewed because it encompasses the activities/decisions addressed in this thesis.

Numerous textbooks provide definitions of logistics. Christopher (1998) uses the following definition as a starting point: ‘Logistics is the process of strategically managing the procurement, movement and storage of materials, parts and finished inventory (and the related information flows) through the organization and its marketing channels in such a way that current and future profitability are maximized through the cost-effective fulfilment of orders.’ According to the Council of Supply Chain Management Professionals (www.cscmp.org), ‘Logistics management is that part of supply chain management that plans, implements and controls the efficient, effective forward and reverse flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers’ requirements.’ Frazelle (2002) uses a simple definition: ‘Logistics is the flow of material, information and money between consumers and suppliers.’

A number of elements seem to appear in most definitions of the logistics concept:

- **Management.** Management involves planning, leading, organizing and controlling an organization’s human and capital resources in order to accomplish its objectives (Hanna and Newman 2001). According to Simon (1977), the whole process of management is about *decision-making*. Decision-making can be defined as the process of choosing alternative courses of action for the purpose of attaining a goal or goals (Turban et al. 2007).

- Efficient and effective **flow and storage of material and related information** and (in some definitions) money. Materials usually flow downstream from suppliers to customers and include raw materials, components, sub-assemblies and finished goods. Upstream material flows can consist of end-of-life returns, recycled materials, scrap from production etc. Related information typically flows upstream, such as customer orders, forecasts and replenishment orders. More recently, the potential benefits from sharing additional information in both directions has also been recognized, such as inventory levels, capacities and point-of-sales data. There are also information flows between different logistics planning/control tasks. Aggregate tasks provide input for more detailed tasks, which in turn provide feedback on actual performance (see Fleischmann et al. 2005).
- **Systems perspective**, from suppliers through internal functions all the way to final customers (point-of-origin to point of consumption), aiming at sound solutions for the system as a whole. In such a perspective, all functions, facilities and actors that play a role in making the final product available to the customer are taken into consideration. Solutions are sought that are cost-effective for the system as a whole. This requires a holistic view, because if each entity optimizes its operations individually, the total system performance may not be optimal. This understanding lies at the heart of the supply chain management concept.
- Goal of **satisfying customer requests (the right products to the right place at the right time) at lowest possible cost**. The whole purpose of logistics is to provide customers with the level and quality of service that they require and to do so at less cost to the total supply chain (Christopher 2005). Thus, the customer view is crucial in logistics (as well as all other business functions) because processes are ultimately carried out to satisfy the customer. At the same time, costs need to be kept as low as possible. This implies that an important issue in logistics is balancing contradicting goals, i.e. finding **trade-offs** between customer service levels and logistics costs. For example, high inventory levels can improve product availability, but they increase inventory carrying costs. Similarly, reduced transportation lead times decrease delivery times, but can increase transportation costs.

Logistics can thus be defined as follows:

Logistics is the management of material and related information flows in organizations, aiming at the efficient and effective flow and storage of raw materials, in-process inventory, finished goods and related information from point-of origin to point-of-consumption for the purpose of conforming to customer requirements at lowest possible total cost.

From this definition, it can be seen that logistics plays an important role within operations management. Operations management is about managing input-transformation-output processes, and such processes are made possible through flows of material and information. Managing the flow of material and related information is thus crucial for effective operations management. Moreover, material/information flows span across functional and organizational boundaries, and their effective management inherently necessitates a process rather than functional view. This is in accordance with the now common, broad view of operations management.

The logistics concept is also closely related to supply chain management. In particular, both take a broad view from point-of-origin to point-of-consumption and aim at systemwide,

effective solutions satisfying the customers. Lambert and Cooper (2000) discuss the two concepts in relation to each other. They explain that supply chain management is about integrating key business processes across the supply chain. Logistics is an important area for integration, i.e., integrating material and related information flows. It plays a key role in several of the business processes they identify, in particular order fulfilment, manufacturing flow and procurement. But, as explained above, there are numerous other processes that benefit from integration and are addressed by supply chain management. The definition of logistics management provided by the Council of Supply Chain Management Professionals explicitly underpins this view by stating that logistics is *a part of* supply chain management. Thus, in logistics, focus is on effective material flows, in supply chain management, focus is on process integration.

Even though logistics has been a decisive activity in the military throughout the history of mankind, it is only in the recent past that business organizations have truly recognized the impact logistics can have to achieve competitive advantage (Christopher 2005, Frazelle 2002). Today, it is considered one of the most important activities in modern societies (Ghani et al. 2004). Both in the EU and the USA, total logistics costs represent over 10% of the Gross Domestic Product (Ghani et al. 2004, Frazelle 2002, respectively). In addition to cost reduction, the recent focus on logistics is motivated by an understanding that logistics can provide an important competitive advantage (Christopher 2005, Bowersox et al. 2002). Companies who have developed effective and efficient logistics processes achieve superior customer service at minimum cost. Thus, the key advantage of focusing on logistics lies in its ability to simultaneously reduce costs and improve customer service.

Most manufacturing companies today have a department responsible for the flow of materials, even though other names than logistics may be used, such as materials management and distribution planning and control. The term materials management is also used in some textbooks, for example Arnold et al. (2008).

Slack's (2007) division of an organization into three core functions can be used to place logistics within the organization (Figure 3-2). As explained above, logistics plays an important role in the management of operations, and it can be considered as part of operations. Quality control and maintenance are examples of other functions within operations. Logistics has important links with the sales/marketing and the product/service development function. For example, sales/marketing provides logistics with product forecasts, i.e. key information about expected future sales in different markets. So, in this framework, forecasting is not considered as logistics itself, but as providing important *input data* for logistics. In products/service development, it is crucial to take into consideration logistics aspects, as they will heavily affect the cost of producing and delivering the product/service. Thus, Figure 3-2 can be used to define the scope and interfaces of logistics as it is used in this thesis.

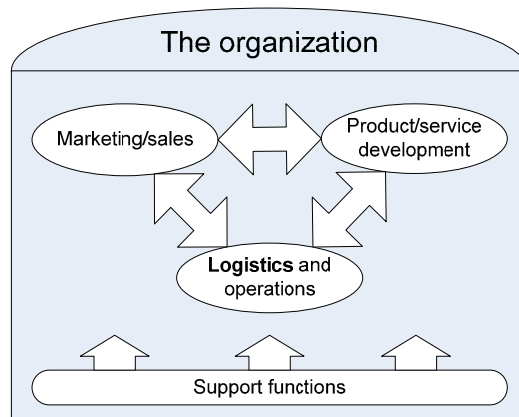


Figure 3-2: Placing logistics into a larger organizational context (Slack et al. 2007)

Logistics activities can be described by means of processes, i.e. planned series of actions or operations that advance a material or procedure from one stage of completion to another (APICS dictionary). Jonsson (2008) identified six processes which are normally most central to logistics:

- Order-to-delivery: From customer order received to invoiced dispatch
- Supply: From identified material need to received and approved delivery
- Manufacturing and service: From identified need to performed, accessible and approved added value
- Distribution: From physically accessible product to distribution of product on site to customer
- After sales: From delivered product or service performed to expiry of guarantee or agreement
- Return: From identification of return need to received return consignment at recipient

Each of these processes consists of activities and decisions. Figure 3-3 shows some examples.

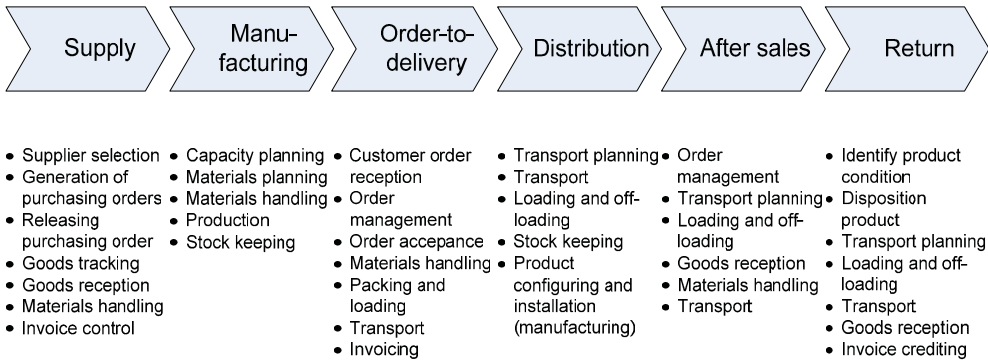


Figure 3-3: Key processes in logistics, with examples of activities/decisions (Jonsson 2008)

In addition to being a set of processes and activities/decisions, logistics provides a *perspective* to view an organization and its supply chains. In this perspective, focus is on material flows and related information flows, on the way these flows are controlled and on how they can be improved so that customer service is increased and costs decreased. This perspective is at the heart of the Control Model Methodology developed by NTNU/SINTEF. In this methodology, the current material and information flows and control principles, the AS-IS control model, are first mapped and analyzed. This leads to the identification of improvement areas and the development of new solution elements. These elements are used to develop the future state, the TO-BE model. Design and implementation of the TO-BE model are carried out in an iterative process. A control model for aluminium bumper production at Hydro Aluminium Automotive Structures (HAST) is shown in Figure 3-4 (Alfnes et al. 2006).

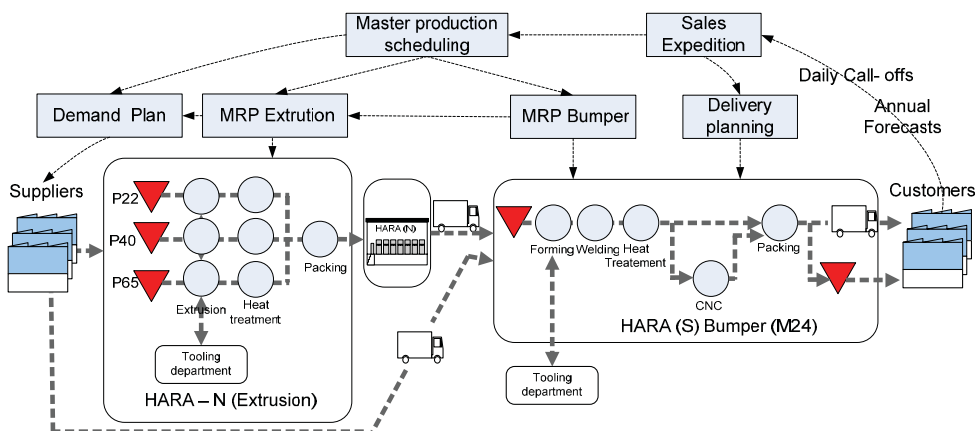


Figure 3-4: Example of a control model (Alfnes et al. 2006)

As explained above, logistics is concerned with management, which is basically about decision-making. Logistics decisions have different planning horizons, from short-term to long-term, and they concern systems of varying extension, ranging from single pieces of

equipment all the way to global networks. A number of classifications of logistics decisions are now reviewed.

3.2.1 Planning horizons

Logistics decisions can have different planning horizons (temporal scopes). A well-established hierarchy classifying decisions according to their planning horizon is the one usually associated with Anthony (1965). He defined three planning levels: strategic planning, tactical planning (originally called management control) and operational control. *Strategic planning* refers to long-term decisions (from 2 to 10 years ahead), which – as a consequence – deal with high uncertainty and risk, have long-term effects and large, company-wide consequences. Such decisions are taken by senior management and can be decisive for a business' success or failure. At this level, information is processed at a highly aggregated level. *Tactical planning* has a planning horizon of approximately three months to two years; the degree of uncertainty and risk is medium, as well as the scope of its consequences. Middle management is responsible for this planning level, using moderately aggregated information. *Operational control*, finally, has a short-term perspective and aims at the execution of the tactical and strategic plans. It is carried out daily, often at a local level and with a low degree of risk and uncertainty. Such decisions are taken by lower management and require complete disaggregation of information.

Table 3-1: Characteristics of the three planning levels usually distinguished (based on Anthony 1965)

	Strategic	Tactical	Operational
Horizon	long-term 2 – 10 years	medium-term 0,5 – 2 years	short-term < 0,5 years
Consequences	large	medium	small
Uncertainty	high	medium	low
Management level	top	medium	low
Data aggregation level	high	medium	Low
System scope affected	often large	often medium	often small

As an illustrating example of these three decision levels in the context of logistics, imagine a chair manufacturer using screws to assemble its chairs. Imagine further that these screws are purchased from an external supplier, and that the manufacturer uses a simple (Q, R) policy to control its inventory of screws – whenever the inventory level falls to a reorder level R, place an order for Q units (see Simchi-Levi et al. 2008 for details). The decision to procure screws externally instead of producing them internally (make-or-buy decision) is a rather strategic decision. The choice of using a (Q, R) policy would typically be tactical decision. Finally, deciding actual order quantities and placing orders to the supplier would be operational tasks.

Anthony's (1965) way of grouping decisions into three levels according to their temporal scope is well known today and frequently used in both practice and theory. It is also used as a rough structure in more detailed classifications of logistics decisions and activities, such as several of the ones reviewed below.

A second common and useful classification into different time horizons uses just two classes: *design* and *operation*. Design involves irregular, long-/midterm decision-making aiming to

establish or improve operation; operation includes activities carried out regularly and frequently (mid/short-term planning). Smith (2003) uses this classification, for example. Plant location, supplier selection, and the determination of inventory control principles are typical design decisions. Operation includes, for example, short-term production planning/scheduling and determining actual inventory replenishment times and quantities.

3.2.2 Structure – control

Another basic way of structuring logistics decisions distinguishes between *structure* and *control* (Jonsson 2008, Semini 2004, Strandhagen et al. 2002). Structural decisions concern the structure of the logistics system, all from the overall supply chain to each single business unit. Examples include the selection of suppliers and carriers, localization of production and warehouse facilities and the physical arrangement of equipment and personnel in each business unit. Such tasks are often of a strategic/tactical nature. In control-related decisions, the structure of the logistics system is considered as given. Focus is on planning and executing incoming deliveries, production and transportation/distribution. Decisions include long/mid-term production and capacity planning and the selection of production control principles. They also include operational, short-term tasks such as daily production planning, production control and initiating transportation of materials between facilities and production units.

3.2.3 System scopes

Logistics decisions can also be classified according to the scope of the physical system they address. Frazelle (2002) distinguishes between five levels in logistics: Workplace logistics, facility logistics, corporate logistics, supply chain logistics and global logistics. In the context of simulation studies, McLean and Leong (2002) define a hierarchy consisting of the levels economy, market, supply chain, enterprise, facility, department, line/area/cell, station, equipment, device and process.

Wu et al. (1997) developed a taxonomy that characterizes research problems in manufacturing logistics. One of the dimensions in this taxonomy concerns the physical system. They distinguish between the four levels production unit, production facility, enterprise and supply chain. The following classification is based on this work and illustrated in Figure 3-5:

- *Unit* – The production unit is the basic entity of the manufacturing system. This can be a single piece of equipment, a workstation, a buffer or a physical grouping of several workstations and equipment such as a manufacturing line or area, a job shop or a flexible manufacturing cell.
- *Plant* – In a plant, several units are gathered at one geographical location and integrated by a certain means, such as vertically by corporate organization, or horizontally by products. A warehouse is also considered as a plant.
- *Supply chain owned by a single organization* – At this level, at least two geographically separated plants or warehouses owned by the same organization are considered. The term ‘network’ would actually be more appropriate since the different plants can represent the same manufacturing/distribution stage.
- *Supply chain owned by several independent organizations* – At the broadest level, the scope covers a supply chain consisting of several independent organizations. These

organizations cooperate to deliver end products. Typical actors in supply chains include suppliers, manufacturers, distributor, retailers and end customers.

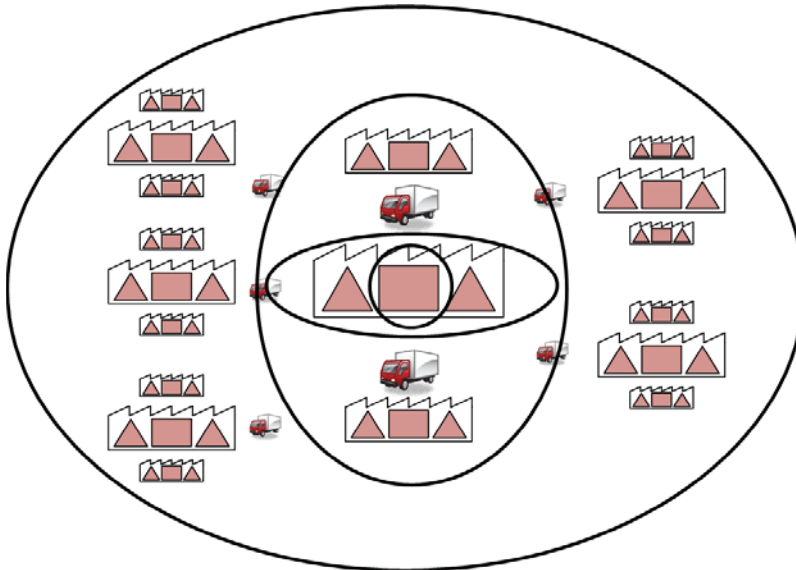


Figure 3-5: Manufacturing logistics decisions can have four different system scopes: Unit, plant, supply chain owned by a single organization or supply chain owned by several independent organizations.

This section has introduced numerous facets of the logistics because they are important to understand manufacturing logistics and the remainder of this thesis. The other key concept is manufacturing, which will be presented next.

3.3 Manufacturing

At the beginning of this chapter, a distinction was made between manufacturing operations and service operations. This thesis focuses on manufacturing operations, so the concept of manufacturing will now be looked at more closely.

The APICS dictionary defines *manufacturing* as a series of interrelated activities and operations involving the design, material selection, planning, production, quality assurance, management and marketing of discrete consumer and durable goods. In manufacturing, physical goods are produced, i.e. raw materials are processed into intermediate materials, which are further transformed into components and, ultimately, finished end products. Companies/organizations involved in this physical transformation process are called *manufacturing companies/organizations* (In this thesis, the terms company and organization are used interchangeably). Often, numerous manufacturing companies are involved before the raw materials are completely transformed into the end product. Some manufacturing companies are vertically integrated and carry out large parts of this process; others just make a small contribution.

In the automotive industry, for example, hundreds or thousands of companies are involved before a car leaves the final assembly plant. Cars consist of thousands of components, and each component may itself have been produced by a series of manufacturing companies. In

order to produce an aluminium bumper beam, for example, bauxite needs to be extracted in mines first. Various grades of bauxite are then mixed, heated, and cast into ingots of different sizes. Next, the ingots are melted again and cast into billets, which prepares the next process, extrusion. In extrusion, the billets are transformed into profiles of various shapes, which are cut into appropriate lengths. These profiles are then stretch bent and heat treated. The resulting bumper beam may then be welded and assembled into a car sub-system, which may itself be assembled into a larger sub-system. In final assembly, sub-systems and components are put together, which results into a finished car (Figure 3-6).

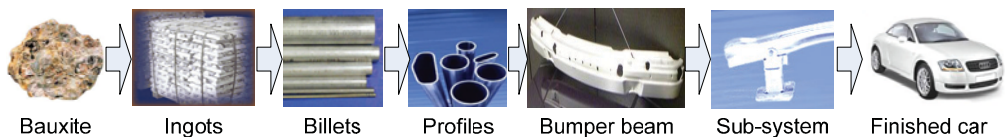


Figure 3-6: The main stages in the manufacturing process of aluminium bumper beams used in cars

In other industries, one single company can sometimes carry out much of the physical transformation itself. The Norwegian fish hook manufacturer Mustad, for example, buys raw wire from external suppliers, but is in charge of the remaining transformation processes necessary to produce consumer-packaged fish hooks: Wire drawing, machining, hardening, surface treatment, assembly (for some products) and packaging.

The APICS dictionary can also be used to clarify the difference between manufacturing and production. *Production* refers the physical conversion of inputs into finished products. It is part of manufacturing, but manufacturing also covers numerous other activities, such as design, material selection, planning, quality assurance and marketing.

One common way to classify manufacturing operations (and manufacturing companies) is according to the *industry* they belong to. Several standards have been developed for industry classification, including the Global Industry Classification Standard (GICS) and the North American Industry Classification System (NAICS). For the following reasons, this thesis uses NAICS:

- Some of the key literature sources used in this research are American (the journal *Interfaces* and the proceedings of the *Winter Simulation Conference*), and it is natural to publish results in these same sources.
- NAICS has a user-friendly web page (www.census.gov/naics). On this web page, the entire classification system is available. A search engine allows quick identification of the correct classification number for any given product.
- Other researchers suggest it, for example McLean and Leong (2002).

NAICS was developed jointly by the governments of the United States, Canada and Mexico to provide new comparability in statistics about business activity across North America. It allows researchers to make better analyses and comparisons of different industries. NAICS is based on a 6-digit code. The code prefixes 31-33 denote manufacturing industries. Table 3-2 shows the complete list of 3-digit codes in manufacturing.

Table 3-2: The entire list of 3-digit codes the North American Industry Classification System uses to classify manufacturing industries

311	Food Manufacturing
312	Beverage and Tobacco Product Manufacturing
313	Textile Mills
314	Textile Product Mills
315	Apparel Manufacturing
316	Leather and Allied Product Manufacturing
321	Wood Product Manufacturing
322	Paper Manufacturing
323	Printing and Related Support Activities
324	Petroleum and Coal Products Manufacturing
325	Chemical Manufacturing
326	Plastics and Rubber Products Manufacturing
327	Nonmetallic Mineral Product Manufacturing
331	Primary Metal Manufacturing
332	Fabricated Metal Product Manufacturing
333	Machinery Manufacturing
334	Computer and Electronic Product Manufacturing
335	Electrical Equipment, Appliance, and Component Manufacturing
336	Transportation Equipment Manufacturing
337	Furniture and Related Product Manufacturing
339	Miscellaneous Manufacturing

Industry classifications are basically classifications of the *products* manufactured. Other ways to classify manufacturing operations according to their products (i.e., the output of the manufacturing process) include:

- Volume: From low-volume to high-volume
- Variety: From low-variety to high-variety

These two dimensions usually go together. If there are many product variants, the quantity of each variant is usually low. Examples include ships or oil platforms. If there are few product variants, each variant is usually produced in high quantity. Typical examples are paper, food and chemicals.

In addition to classification according to the products produced, manufacturing operations can also be classified according to the *manufacturing process*. Process types typically include project, jobbing, batch, mass and continuous (see Slack et al. 2007). Product and process type are not independent, but related to each other in the product-process matrix (Hayes and Wheelwright 1979). According to Hayes and Wheelwright (1979), it is most effective to position the manufacturing system along the diagonal from the top left-hand to the bottom right-hand corner. For low-volume, one-of-a-kind products, high flexibility is needed and a project process is therefore most suitable. For high-volume commodities, automation and effectiveness are more important than flexibility, so a continuous process fits best. Even though recent concepts such as mass customization indicate that positioning in the lower left-hand corner may be an ideal to aim for (see for example Gilmore and Pine 1997), the matrix still indicates how different product and process types are related (Alfnes 2005).

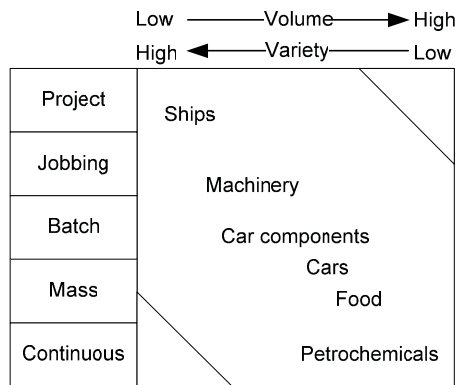


Figure 3-7: The product-process matrix (based on Hayes and Wheelwright 1979) with some product examples

To a certain extent, the matrix thus relates process types to different industries. For example, food and chemical industries typically use mass and continuous processes; the construction of a ship is organized as a project. In many cases, however, the three-digit level of the NAICS classification is too superficial to allow positioning in the product-process matrix. For example, transportation equipment manufacturing includes both low-volume ship manufacturing and high-volume car manufacturing. Both product type and process type should therefore be investigated when studying the characteristics of a manufacturing process.

3.4 Manufacturing logistics

The main aspects relevant to the concept manufacturing logistics have now been introduced. In this thesis, manufacturing logistics is defined as the logistics decisions made in manufacturing companies. The focus in manufacturing logistics is on transformation of material, and how this transformation can be done effectively and according to customer requirements. Transformation is here used in a wide understanding, including all activities modifying the material itself or giving it a time/space value for the customer, such as production, assembly, transportation and storing. So, all the manufacturer's decisions getting the right product to the right place at the right time are considered as manufacturing logistics. The manufacturer is considered as the focal company and material/information flows are considered from this perspective. Manufacturing logistics takes a broad view, encompassing also decisions involving suppliers and customers that contribute to making the final product available to the end-customer. The supply chain is therefore often viewed as in Figure 3-8 (Lambert et al. 1998). This broad view of manufacturing logistics, including the entire supply chain from point-of-origin to point-of-consumption, follows the trend in operations management.

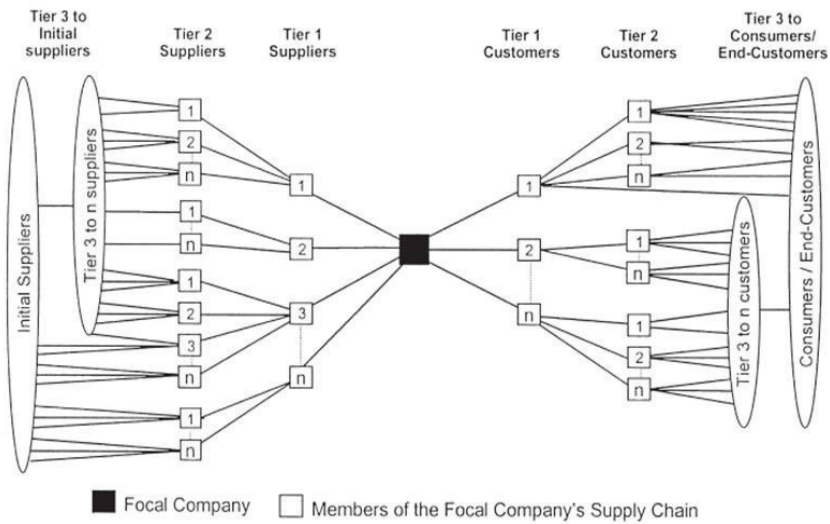


Figure 3-8: A supply chain consisting of a focal company and several tiers of suppliers and customers (Lambert et al. 1998)

Wu et al. (1999) also define manufacturing logistics with such a broad view, declaring it to be all planning, coordination and service functions required to carry out manufacturing activities; with a scope beginning from the point where end-item customer demands are determined, and extending to where the demands are fulfilled; and considering the flow of material and information across enterprise, industry and national boundaries. They view manufacturing logistics as an academic research area encompassing many aspects of operations management and supply chain logistics.

Some literature takes a narrower view of manufacturing logistics. In German and Scandinavian literature, for example, manufacturing logistics ('Produktionslogistik') is often primarily concerned with material and information flows from raw material inventory through production to finished goods inventories *within* a plant (for example Mattsson and Jonsson 2003, Scheer 1998, Zäpfel 1991, and Lenz 1988). In such a view, manufacturing logistics is distinguished from *procurement logistics* and *distribution logistics*, where the former is responsible for material flows from suppliers into the factory, the latter for material flows of finished goods out of the factory to the customers. The interrelationships between these subsystems are, however, recognized and accounted for. The three subsystems together constitute the area of logistics in an industrial organization.

Manufacturing logistics, as defined in this thesis, includes a wide range of aspects, which all affect the material and related information flows in the manufacturing environment. Together, they determine its performance in terms of cost, speed, quality, flexibility etc. Table 3-3 contains numerous such aspects, organized into seven categories (Semini et al. 2004).

Table 3-3: Important aspects of manufacturing logistics (Semini et al. 2004)

Market	Order variation and change	Data acquisition
No. of customers	Customer order handling	Dedicated equipment
Type of customer	Customer order integration	Capacity utilization
Type of contract	Shop floor system approach	Bottlenecks
Price elasticity	Control techniques	No. of work shifts
Market requirements	Supplier orders means of comm.	Set-up time
Competitive strategy	Suppliers info sharing	Operational time
Market location	Replenishment order frequency, volume	Throughput time
Demand variation	Replenishment order changes and variations	Production lot sizes
Demand uncertainty	Replenishment order integration	Transfer quantity
Competitive situation	Decision level	Waste/wreckage
Demand volume	Workforce structure	Preventative maintenance
		Training
Product	Procurement	Distribution
Product variety	Share of total turnover	No. of drop points
New product development	Sourcing strategy	No of distribution echelons
Product launching	Components customization	Actors in distribution channel
Customization	Number of suppliers	No. of actors at each echelon
Market relation	Supplier location	No. centralization and locations of warehouses
Added value Service	Replenishment principles	Terminal operations
Monetary density	Inbound Transport pattern	Inventory turnover rate
Product life	Supply frequency	Inventory costs
Transportation and handling requirements	Terms of delivery	Delivery principles
Hygiene requirements	Type of contract	Transport frequency
No. of BOM components	Inbound transportation mode	Transport mode
Modularity		Outbound transport pattern
Levels in BOM	Manufacturing system	Term of delivery
I V A X structure	Shop floor layout	3pl service provision
Environmental considerations	Process choice	3pl Contract period
Life cycle	Redundancy	
	Parallel/serial assembly	Relations
Control strategy	WIP centralization	Vertical integration
CODP	Buffer levels	Dominance
Material planning approach	Tool store centralization	Level of collaboration
Customer orders means of communication	Operative vs. administrative workforce	Stability in value chain
Info sharing with customer	Level of automation	Profit distribution
Customer order frequency and volume	Capability	

The product and market categories contain aspects whose main responsibility lies at the product development function and the sales/marketing function, rather than operations. These aspects are often considered as given when manufacturing logistics develops and assesses solutions for effective operations. It is, however, important to consider operational aspects in product development and sales/marketing decisions. This is, for example, achieved by means of concurrent engineering (Smith 1997). The next four categories in Table 3-3 contain aspects for which manufacturing logistics attempts to develop effective solutions. The control strategy relates to the way material and related information flows are planned and controlled. Inbound and outbound logistics are covered by the procurement and distribution categories, respectively. The manufacturing system refers to the physical structure of the production system and its performance. The final category, relations, includes inter-organizational

aspects between the different actors in the supply chain, i.e. the type of relationship they have with each other and how it is organized. Such aspects are of relevance for the success of the supply chain as a whole, and they are often addressed at high managerial levels. They can crucially affect the effectiveness of manufacturing logistics and operations. Meyr and Stadler (2005) have developed a similar categorization of attributes that can be used for a supply chain typology.

An example of a key aspect in manufacturing logistics is the customer order decoupling point (CODP), also called market interaction point. This point separates order-based production from forecast-based production. Upstream of the customer order decoupling point, standard products or parts are produced before an actual customer has requested them. Downstream of the point, all activity is completely driven by a specific customer's requests. The customer order decoupling point is often a natural point to store materials/products until a concrete customer order requires them. Appropriate setting of the customer order decoupling point depends on market, product and process characteristics, and it can provide companies with an important competitive advantage. The main types distinguished are make-to-stock, assemble-to-order, make-to-order and engineer-to-order. Figure 3-9 shows the placement of the decoupling point in each case (Browne et al. 1996).

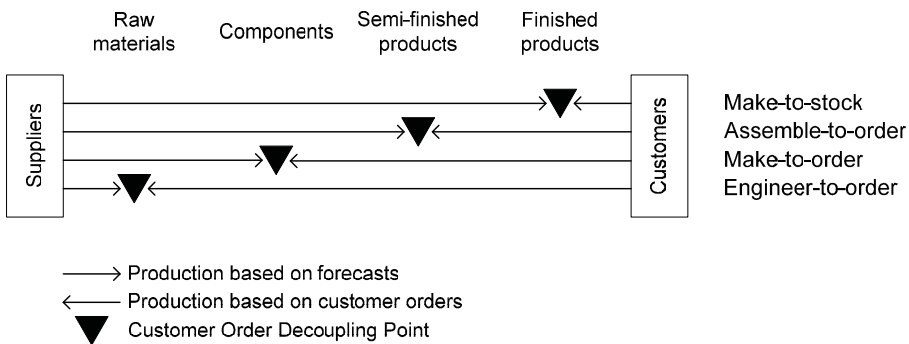


Figure 3-9: Positions of the customer order decoupling point (Browne et al. 1996)

A basic understanding of manufacturing logistics has now been elaborated. The next section builds upon it by focusing on the typical decisions manufacturing logistics involves.

3.5 Frameworks of manufacturing logistics decisions

In order to provide a more detailed appreciation of the decisions and activities belonging to manufacturing logistics, a number of well-known frameworks are now reviewed that organize and structure them and show their relationships. An important purpose of the present review is also to prepare the development of a classification of manufacturing logistics decisions supported by OR, which will be done in Chapter 6. The frameworks reviewed here are of particular relevance in this respect because they are made from the perspective of IT-based (decision) support and, thus, likely to provide good starting points.

The researcher agrees with Chan (2005) that the manufacturing planning and control (MPC) system is one of the significant parts of manufacturing logistics. Vollmann et al.'s (2005) established MPC system framework is therefore reviewed first. In order to also gain an

understanding of MPC in just-in-time/pull environments, the framework by Hopp and Spearman (2001) is briefly reviewed.

The MPC frameworks have emerged from a unit/plant perspective rather than a supply chain view. In order to cover manufacturing logistics decisions at the supply chain level, the framework for 'IT capabilities required for supply chain excellence' (Simchi-Levi et al. 2008) is brought forward next. Finally, the Supply Chain Planning Matrix (Fleischmann et al. 2005) is studied because it integrates decisions of all system scopes and is as such particularly appropriate to structure manufacturing logistics decisions.

These frameworks provide a structured overview of key activities and decisions in manufacturing logistics. It should however be noted that they focus on what can be supported by IT systems. It is important to realize that manufacturing logistics also concerns other decisions, for example related to performance measurement system design and administrative process design. Developing a comprehensive framework of manufacturing logistics activities/decisions would be an interesting path of further research.

3.5.1 The manufacturing planning and control system

The manufacturing planning and control (MPC) system is concerned with planning and controlling all aspects of manufacturing, including managing materials, scheduling machines and people and coordinating suppliers and key customers (Vollmann et al. 2005). A firm's MPC system is not static, but needs to be adapted continuously to changes in its environment, such as markets, products and technology.

Undoubtedly, the MPC system plays an important role in manufacturing logistics. Many central issues within manufacturing logistics concern the MPC system. An understanding of the tasks and decisions addressed by the MPC system therefore provides an insight into key issues within manufacturing logistics. Major tasks within the MPC system are now briefly introduced by means of two frameworks from the literature.

The traditional MPC planning framework

Vollmann et al. (2005) propose a frequently used framework of activities within the MPC system (Figure 3-10). It consists of three phases, the front end, the engine and the back end. The front end is concerned with the overall company direction for manufacturing planning and control. Demand management covers all activities that place demand on manufacturing capacity, such as forecasting and order entry. Sales and operations planning balances sales/marketing plans with production resources. It is a tactical activity carried out in collaboration between manufacturing, marketing and sales, procurement and other departments, resulting in an agreed-on company plan. The master production schedule is a translation of the sales and operations plan into end items to be produced by manufacturing. It supports the sales and operations plan and provides key input for more operational MPC activities (engine and back end). Resource planning is concerned with mid-term capacity planning, assuring the company has enough capacity to produce the required products.

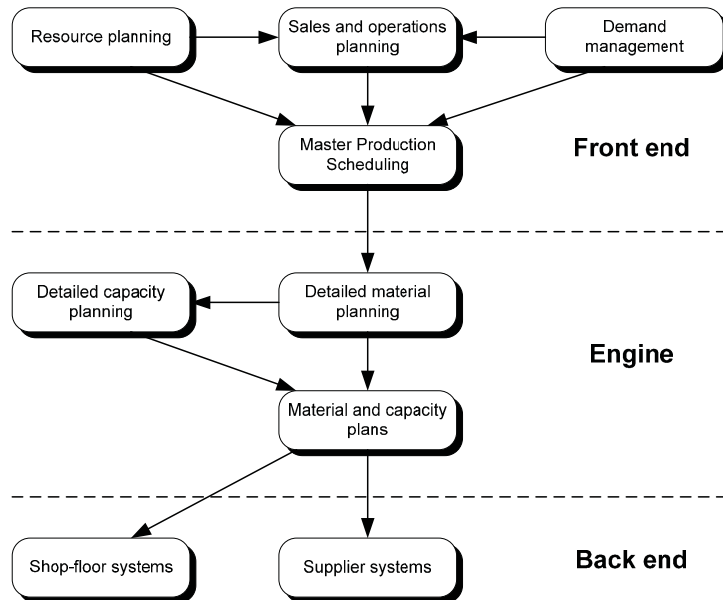


Figure 3-10: The traditional MPC framework (Vollmann et al. 2005)

The engine consists of more detailed material and capacity planning. Detailed material planning uses the master production schedule to calculate components and raw material required in each time period. Often, this entails detailed material requirements planning (MRP) calculations (see for example Chapter 7 in Vollmann et al. 2005). In detailed capacity planning, the material plans are checked for capacity feasibility. If the required labour or machine capacity cannot be made available, the material plans may have to be changed. The output of this MPC phase is detailed, operational plans of what to produce where and in which time period (such as days). It is input to the third phase, the back end, which consists of execution systems. They include shop-floor systems for detailed scheduling/sequencing of each single resource, making detailed plans available on the shop floor in real-time. An important function of such systems is feedback on shop performance against plans. Execution also covers order release, authorizing release of individual orders to the factory and providing necessary documentation. Supplier systems communicate detailed production data with suppliers, such as purchase orders and future plans. If parts of production are carried out at other sites, detailed schedules may need to be coordinated.

This framework takes the perspective of Enterprise resource planning (ERP) systems, which are built around the traditional Material Requirements Planning (MRP) approach to planning (see Orlicky 1975). ERP systems usually include different modules for the activities distinguished in the framework. Thus, Vollmann et al.'s (2005) framework is for example useful when discussing MPC functionality in ERP systems. The framework is also used, with some minor modifications, by the Association for operations management (APICS) as a reference model in its educational programmes (www.apics.org). More generally, its structure terminology can to some degree be recognized in many textbooks treating manufacturing planning and control (such as Arnold et al. 2008, Jonsson 2008, and Higgins et al. 1996).

A pull planning framework

Hopp and Spearman (2001) propose a framework with a similar scope, but adapted to pull systems, i.e. manufacturing systems that carry out planning according to just-in-time and related principles. See for example Chapter 4 in Hopp and Spearman (2001) for details about just-in-time and pull systems. Figure 3-11 shows their ‘production planning and control hierarchy for pull systems’. It consists of planning tasks in rectangular boxes, and input/output from these tasks in rounded boxes.

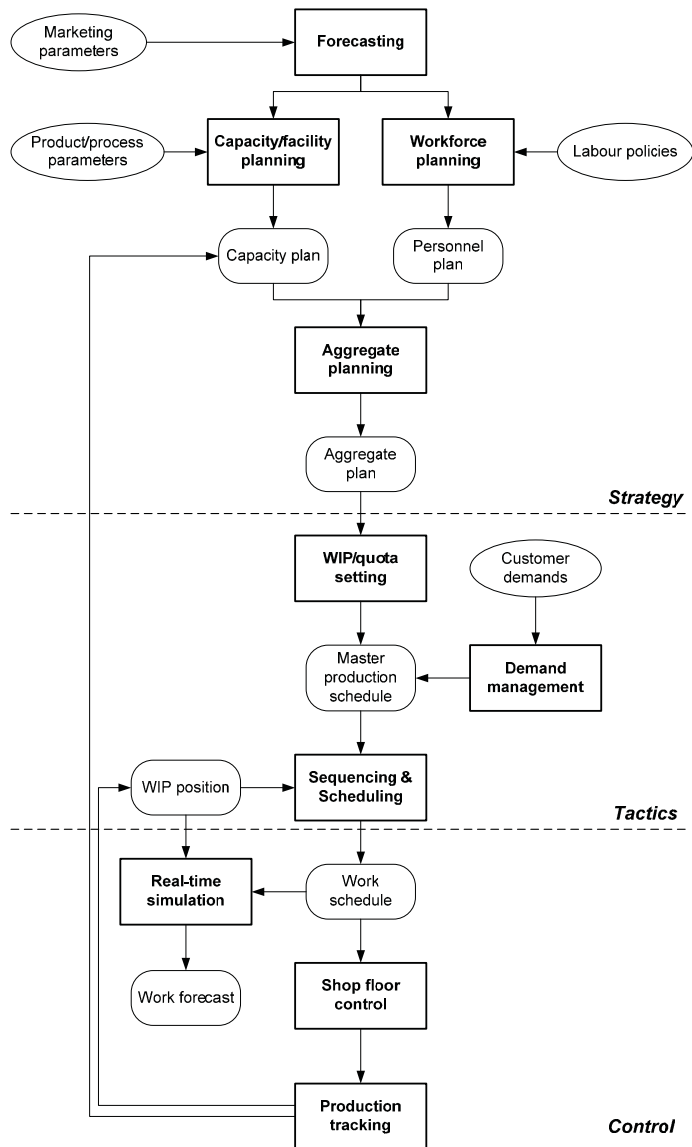


Figure 3-11: A production planning and control hierarchy for pull systems (Hopp and Spearman 2001)

The framework is structured hierarchically into what these authors call strategy, tactics and control. Strategy includes forecasting, capacity/facility planning (physical equipment), and aggregate planning (indicating future production mix and volume). These tasks largely correspond to the front end activities in Vollmann et al.'s framework, besides master production scheduling, which is only done after a WIP/quota setting determining KANBAN card counts and periodic production quotas in the pull system. The typical Engine tasks in Vollmann et al., detailed material and capacity planning, are left out since they typically are much simpler or can be skipped in pull systems. On the other hand, an increased focus is on short-term planning and control activities, including sequencing & scheduling, shop-floor control, real-time simulation for what-if analysis and production tracking.

The MPC frameworks presented above include several key activities within manufacturing logistics. They also show that the role and importance of these activities depend on how the MPC system is designed (for example push or pull), and they therefore vary from company to company. On the other hand, they do not cover the entire area of manufacturing logistics. They focus on control issues, only marginally addressing decisions related to the structure of the manufacturing system. Moreover, they ignore more strategic decisions related to control, for example selecting appropriate control systems and principles. Furthermore, focus is on production, and activities such as inventory and transportation management are not explicitly included. Finally, decisions concerning several plants and organizations are missing, as Vollmann et al. (2005) remark themselves. Examples of such activities include vendor managed inventory (see Simchi-Levi et al. 2008) and coordinated mid-term production and capacity planning. The frameworks presented in the following have a wider scope.

3.5.2 IT capabilities for supply chain excellence

Simchi-Levi et al. (2008) present a framework of supply chain tasks addressed by IT (Figure 3-12). They consider these tasks to be 'IT capabilities necessary for supply chain excellence'. The framework consists of four layers, which differ in planning horizon, return on investment and implementation complexity.

- *Strategic network design*: Determine the number, location and size of plants and warehouses, what to produce where, which customers to serve from which warehouses. Minimize total costs, including sourcing, production, transportation, warehousing and inventory.
- *Tactical planning*: Resource allocation for the next weeks or months. *Supply chain master planning* coordinates production, distribution and storage requirements to maximize profit or minimize costs. *Inventory planning* determines where to keep safety stock and how.
- *Operational planning*: Generate efficient short-term plans for procurement, production, distribution, inventory and transportation. *Demand planning* generates and analyzes forecasts. *Production scheduling* generates detailed production schedules based on tactical plans and forecasts. *Inventory management* generates inventory plans and *transportation planning* is concerned with fleet planning, transportation mode selection and transportation routing and scheduling.
- *Operational execution*: Such systems provide data and process transaction in real-time. They include systems communicating and tracking interactions with customers (customer relationship management) and suppliers (supplier relationship

management), supply chain management systems tracking distribution activities and exceptions and providing lead time quotations based on available-to-promise and capable-to-promise (see for example Arnold et al. 2008 for an introduction to these concepts) and transportation systems, providing access and tracking of goods in transport.

This framework focuses on manufacturing logistics activities that have a scope spanning several plants/warehouses or even several companies. In terms of the logistics system scopes defined in Subsection 3.2.3, it focuses on ‘supply chains owned by a single organization’ and ‘supply chains owned by several independent organizations’.

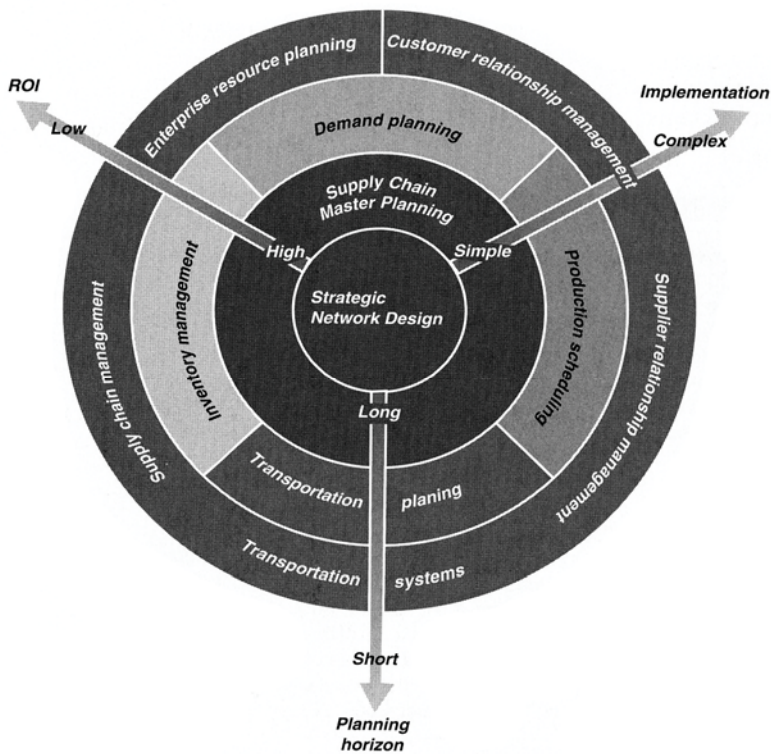


Figure 3-12: Simchi-Levi et al.'s (2008) framework of IT capabilities necessary to achieve supply chain excellence (reproduced with permission of The McGraw-Hill Companies).

Collectively, the frameworks reviewed so far cover many central decisions and activities in manufacturing logistics. They are complementary in the sense that the MPC frameworks focus on the unit/plant level, Simchi-levi's framework on the supply chain levels. The Supply Chain Planning Matrix presented in the next subsection integrates all these levels in one framework.

3.5.3 The Supply Chain Planning Matrix

Fleischmann et al. (2005) propose a framework for ‘planning tasks in supply chains’: The Supply Chain Planning Matrix (Figure 3-13). This framework covers many key decisions in manufacturing logistics. It consists of two dimensions, the planning horizon (long-term, mid-

term, short-term) and the supply chain process (procurement, production, distribution, sales). The thereby resulting matrix consists of 12 entries, where long-term tasks are shown in a single box to illustrate that such strategic activities span across all supply chain processes. Each of the entries has a number of typical tasks, whose importance varies from business to business. Note that the Supply Chain Planning Matrix includes planning activities related to sales, which are not considered as part of manufacturing logistics in this thesis.

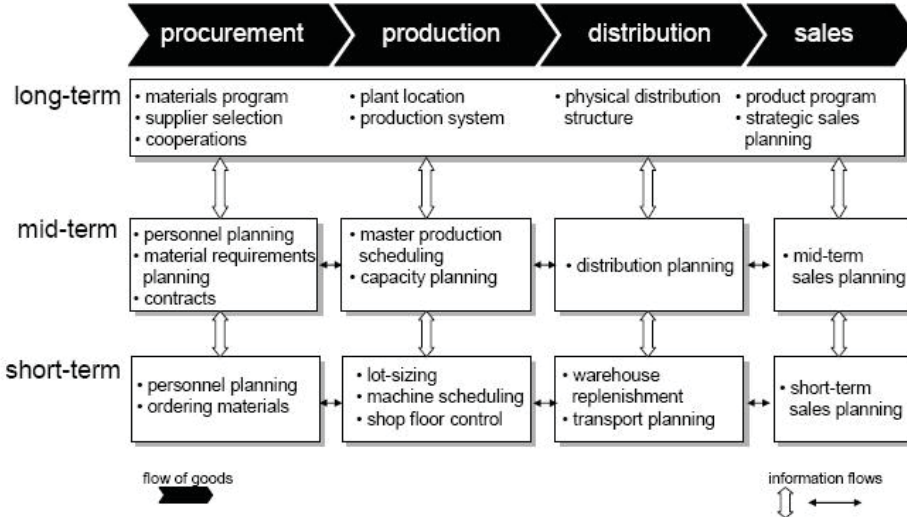


Figure 3-13: The Supply Chain Planning Matrix (Fleischmann et al. 2005)

Long-term activities include selecting materials (if product design allows substitutes) and suppliers, establishing co-operations, plant location, designing plant layout of machines and material flows, determining the number of warehouses, cross-docking facilities and other distribution structure, deciding which products to offer, and in which markets.

Mid-term planning tasks related to sales concern mainly mid-term forecasting. Within distribution planning, key tasks are planning of transports between warehouses as well as determining necessary stock levels. Mid-term production tasks include aggregate production/capacity planning and master production scheduling. Mid-term procurement is concerned with assuring that the necessary personnel capacity as well as raw materials and components are available to complete the master production schedule. This includes monthly order quantities and safety stock levels. Mid-term contracts with key suppliers are also an important issue.

Short-term sales planning is concerned with the fulfilment of customer orders from stock (in make-to-stock situations), using concepts such as available-to-promise. Warehouse replenishment and short-term transport planning is responsible for daily transportation quantities from factories to warehouses as well as from warehouses to customers. Within short-term production planning, key issues are lot sizing, scheduling, sequencing and shop floor control. On the procurement side, detailed staff schedules must be produced, as well as actual replenishment orders to suppliers.

The Supply Chain Planning Matrix also incorporates material and information flows. Material flows go mainly downstream along the four supply chain processes procurement-production-distribution-sales. Information flows can be horizontal as well as vertical. Horizontal flows go mainly upstream, such as customer orders, sales forecasts and replenishment orders. The exchange of additional information in the supply chain leads to horizontal flows in both directions, such as inventory levels, available capacity and point-of-sales data. Vertical flows exchange data between different planning levels. Downward flows coordinate subordinate plans by means of aggregate quantities, capacity allocations and due dates. Upwards flows provide feedback on performance from lower levels, such as costs, production rates, and lead times.

3.6 Summary

This chapter has provided a detailed understanding of manufacturing logistics, i.e. the management of material and related information flows in manufacturing companies. To do so, several relevant concepts have been discussed, in particular operations management, logistics and manufacturing. Operations management is concerned with managing the operations function in organizations. It is the research field within which this thesis has been written. Logistics is concerned with effective material and information flows; it is an important part of operations management. Manufacturing is concerned with processes and activities related to the transformation of raw materials to discrete consumer and durable goods.

Several frameworks of decisions and activities within the scope of manufacturing logistics have also been reviewed. While none of them covers the entire gamut of decisions/activities, they include many core issues and as such provide a good appreciation of what manufacturing logistics is about. The reviewed frameworks are well-known and focus on decisions supported by IT, which makes them good starting points for the development of a classification of decisions supported by OR. This will be done in part III. First, however, the field of OR needs to be introduced and examined in detail. This is the purpose of the next chapter.

4 Operations research

While manufacturing logistics and operations management are about decision-making, operations research is an approach to *support* such decision-making. The present chapter addresses numerous aspects related to operations research and its use in practice. The purpose and need for decision support are addressed first; followed by the way quantitative models can provide such support. The field of operations research is then introduced and defined, as well as the idea of an *OR application*. After some details about different OR subfields, OR is considered from an IT perspective because computers play a key role in its development and use. The way OR is used for decision support is further scrutinized in terms of process and context. Thereafter, the scope is narrowed to this thesis' research issue, the *applicability* of OR techniques. Factors affecting it are considered, strengths and weaknesses of OR discussed and literature reviewed that attempts to characterize the situations in which OR is well applicable. An important section is also the one on technique selection, where it is argued for this thesis' high level perspective, i.e. why OR techniques are grouped into just a few large classes.

4.1 Decision-making and decision support

Decision-making or *problem solving* (terms used interchangeably in this thesis) is a process of choosing alternative courses of action for the purpose of attaining a goal or goals (Turban et al. 2007). A great variety of activities involve decision-making, including planning, organizing and controlling. According to Simon (1977), managerial decision-making is synonymous with the whole process of management.

Many frameworks have been proposed that structure the decision-making process. Each framework takes a slightly different perspective or uses different terminologies, but the essence is very similar in most of them. An often stated, general such framework is the one suggested by Simon (1977). He organizes the decision-making process into the following three phases:

- Intelligence phase: Searching the environment for conditions calling for decision.
- Design phase: Inventing, developing, and analyzing possible courses of action.
- Choice phase: Selecting a particular course of action from those available.

According to Turban et al. (2007), this framework is the most concise and yet complete characterization of rational decision-making. Note, however, that Dewey (1910) much earlier suggested the following, very similar stages for problem solving: What is the problem? What are the alternatives? Which alternative is best?

The purpose of *decision support* is to improve decision-making. 'Improving-decision making' is usually defined as 'making it more effective' (Keen and Scott Morton 1978). Effectiveness is the degree to which goals are achieved; it is concerned with outputs (Turban and Aronson 2001). Applied to the context of decision-making in organizations, it thus means taking decisions that attain intended goals (such as increased profits).

The need for decision support can be usefully explained with the concept of *rationality*. In somewhat simplified terms, one can define rationality as being concerned with the selection of preferred behaviour alternatives in terms of some system of values whereby the consequences of behaviour can be evaluated (based on Simon 1947). Effective decision-

making, then, can be defined as rational decision-making. One can say that decision-making is supported if it is made more rational.

There is a need for decision support because human decision-makers are limited in the extent to which they can act rationally. They may act irrationally although their intention is to act rationally. This is because they are constrained by limited cognitive capabilities and incomplete information; they face serious problems of attention, memory, comprehension and communication (March and Heath 1994). In order to cope with these limitations, decision-makers use various strategies, such as simplifying the problem situation, reducing it into component parts, comparison to familiar situations and rules of thumb. The problem is that such strategies can easily lead to so-called *cognitive biases*, i.e. errors in the way the mind processes information. Examples of such cognitive biases include (Barnes 1984):

- An event is judged as likely or frequent if instances of it are easy to imagine or recall.
- Cause-effect relationships are established based on one or a few instances where some single factor appears to have caused an outcome.
- Overconfidence about judgments made based on rules-of-thumb.

In conclusion, the actions of decision-makers may be less than completely rational because of limited cognitive capabilities and incomplete information. The purpose of decision support is to increase decision-makers' rationality. One way to do so is by means of quantitative models, which are introduced next.

4.2 Models

A model is a simplified representation of a real-world system. It is used as a substitute of the real system. Why using models?

- They facilitate learning and understanding of the real system and its behaviour.
- They facilitate communication by providing a common base for discussions.
- They can reduce the real-world system's complexity to aspects that are relevant to solving a certain problem.

Note that there are numerous more specific advantages of using models, especially of quantitative ones. They will be studied in detail later in this chapter.

According to their level of abstraction, one can distinguish between different types of models (Turban et al. 2007). Three important types are iconic models, analogue models and quantitative models. An *iconic* model is a physical copy of a system, usually in smaller scale. It is often three-dimensional, such as a toy plane or a car. An *analogue* model is a symbolic, usually two-dimensional representation. It behaves like the real system, but does not look like it. Examples include maps, organization charts, bar charts, line graph and drawings. The control model illustrated in Figure 3-4, for example, is an analogue model. *Quantitative* (or *mathematical*) models express a system and its behaviour by means of

- Variables, i.e. measurable quantities of properties of the real system. Often, the following types can be distinguished:

- Decision variables vs. parameters: Decision variables are variables that can be controlled, i.e. modified in the real system, for example production quantities. Parameters are variables that are more inherent in the situation and considered as given, for example demand.
- Input variables (input data) vs. output variables (output data): Input variables are the data collected from the real system and entered into the model, for example production cost per unit. Output variables are the answers obtained from the model, i.e. the data calculated by the model, for example capacity utilization.

Parameters are always input data. Decision variables can be either input or output data, this depends on the type of model (see section 4.5).

- Mathematical and logical expressions relating these variables to each other, such as formulae, equations and inequalities.

Example of a mathematical model: Little's law (see Hopp and Spearman 2001)

Little's law is one of the fundamental principles in manufacturing management. It relates the three variables

- Work-in-process, i.e. the number of items in the system
- Cycle time, i.e. the average time between items leaving the system
- Throughput time, i.e. the average time an items spends in the system

by means of the equation

$$\textit{Work - in - process} = \frac{\textit{Throughput time}}{\textit{Cycle time}}$$

Thus, Little's law says that work-in-process is equal to the ratio between throughput time and cycle time. This law is for example useful when the goal is to reduce work-in-process. It shows that this can be achieved by reducing the throughput time, as long as the cycle time is held constant. Used this way, throughput time is considered as the decision variable, cycle time a parameter and work-in-process the output variable.

This thesis focuses on quantitative models. Quantitative models have been used in many, if not most, scientific disciplines. They range from simple formulae and spreadsheet calculations to complex models with hundreds or thousands of variables and expressions. The way they support managerial decision-making will be scrutinized next.

4.3 Quantitative models for decision support

Quantitative models can help analyze quantifiable factors in a decision-making situation, such as certain costs, times, quantities, frequencies and distances, by relating them to each other with mathematical expressions. They follow the strict rules of rationality given by mathematics and logic and one should thus expect them to be very powerful tools for decision support.

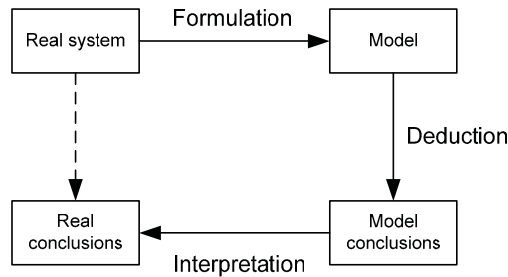


Figure 4-1: The modelling process (Ravindran et al. 1987)

Figure 4-1 shows how quantitative models are used for decision support (Ravindran et al. 1987). When a manager faces a real-world problem situation that requires a conclusion (decision), the simplest approach would be direct judgement solely based on intuition, experience and gut feeling. As an alternative, a quantitative model can be used in an attempt to increase the rationality of the decision. In this case, the first step is to construct the model (Formulation). In this step, it is decided which aspects of the real-world system to include in the model and what assumptions to make. It is often considered as an art as it cannot be defined by any precise procedure. Note that a model can only be formulated *after* formulation of the problem situation. Problem formulation can be an extremely challenging task. It is, however, a very important task because it assures that the model addresses the actual real-world situation of concern. The problem should not be formulated such as to fit certain model structures or properties, otherwise one can end up analyzing the wrong problem (Daellenbach and McNickle 2005).

Once the model is formulated, it can be analyzed (Deduction). Rigorous mathematical and logical procedures are used to draw some conclusions about the model and its behaviour. Examples of such solution procedures include:

- Calculating simple formulae in the input variables (closed-form solutions)
- Solving mathematical equations and inequalities
- Executing mathematical algorithms, i.e. a series of steps or procedures that are repeated (Render et al. 2008)
- Executing a sequence of logical statements
- Trial-and-error, i.e. trying various alternative options and comparing them in terms of output variables

Model analysis also includes so-called what-if analysis and sensitivity analysis:

- In *what-if analysis*, decision variables or parameters are changed and the effect on output variables is observed.
- Similarly, *sensitivity analysis* investigates how changes in certain parts of the model or its data affect the solution (how *sensitive* it is to changes). For example, demand

forecasts or certain cost estimates may be changed in order to see if this critically changes the solutions.

As opposed to the model formulation step, model analysis follows the formal rules of mathematics and logic and the conclusions drawn are not subject to opinion. It requires varying levels of mathematical skills and knowledge about models and solution procedures. In this step, a simplified problem in a simplified world is analyzed and the conclusions drawn are valid primarily in this simplified world.

The concept of model tractability is relevant in this context. Tractability means the degree to which the model admits convenient analysis – how much analysis is practical (Rardin 1998). A closed-form formula directly indicating the best solution is highly tractable because it provides immediate results and rich sensitivity analysis. At the other end of the spectre, if good solutions can only be searched by means of trial-and-error, tractability is low.

The final step, interpretation, requires an understanding of both the real-world situation and of the model. Based on the findings from the model analysis, one now tries to draw some conclusions for the real-world situation. This must be done extremely carefully, as the model is a simplification, built upon certain assumptions which may not hold completely in practice. The concept of validity is important in this context. The validity of a model is the degree to which inferences drawn from the model hold for the real system (Rardin 1998). The more accurately the model represents the real world, the higher its validity. Assessing the validity is a task carried out in collaboration between those who know the real-world problem and those who know the model. Based on this assessment, model conclusions can be followed more or less directly. In most situations, managerial decisions involve factors that cannot be adequately represented by quantitative models, such as behavioural aspects like motivation, emotions and culture. The relevance of such factors is easily seen in strategic issues, such as plant localization, but they are also present in more operational decisions, for example which customer order to prioritize. Considering these factors requires human judgement. Models can therefore only increase the decision-maker's understanding of a problem situation, but usually not replace them. Experience, intuition and internal politics will normally also affect the final decision.

The following anecdotal dialogue between an interviewer and a model analyst at an oil refinery plant illustrates how managers use the information provided by a quantitative model analysis (Little 1970). The term mathematical programming refers to a specific type of model, see Section 4.6.

Interviewer: 'Do you make regular mathematical programming runs for scheduling the refinery?'

Analyst: 'Oh yes.'

Interviewer: 'Do you implement the results?'

Analyst: 'Oh no!'

Interviewer: 'Well, that seems odd. If you don't implement the results, perhaps you should stop making the runs?'

Analyst: 'No. No. We wouldn't want to do that!'

Interviewer: 'Why not?'

Analyst: 'Well, what happens is something like this: I make several computer runs and take them to the plant manager. He is responsible for this whole multi-million dollar plumber's paradise. The plant manager looks at the runs, thinks about them for a while and then sends me back to make a few more with conditions changed in various ways. I do this and bring them in. He looks at them and probably sends me back to make more runs. And so forth.'

Interviewer: 'How long does this keep up?'

Analyst: 'I would say it continues until, finally, the plant manager screws up enough courage to make a decision.'

Little (1970) explains that what the plant manager is doing here is comparing model results to his intuition and finding reasons for discrepancies by inspection, consideration of how the model works and changing input data. Eventually, the manager will agree with the model results and he has learned something new about his problem situation. Little (1970) describes this process as an 'updating of the manager's intuition'. Using the concepts and definitions from Section 4.1, one can say the manager has reduced cognitive biases and increased the rationality of his decision. The quantitative model has supported the manager in decision-making.

4.4 Operations research (OR)

While quantitative modelling certainly has been used to support decision-making for thousands of years, it is generally agreed that its roots as a discipline can be found in the Second World War (Ravindran et al. 1987). Military leaders asked scientists and engineers to analyse complex military problems such as the management of convoy or the deployment of radar. Since the problems were too complex to be solved by a single individual or even a single discipline, interdisciplinary teams were formed, consisting of people with diverse backgrounds such as mathematics, engineering, behavioural science etc. Their purpose was to solve practical problems through the utilization of the 'scientific method'. After the war, many of these team members continued their work. They started to develop a solid theoretical foundation of their knowledge and apply it to civilian problems. Several new disciplines emerged and developed rapidly during the decades that followed. One of them is the discipline concerned with the use of quantitative models to support managerial decision-making, which became known as *operations research* (OR), or *operational research* in the United Kingdom. Since then, OR has been used in many disciplines, including operations management, finance and accounting, human resources, health care and marketing (Winston et al. 2001). Numerous societies have been formed aiming to develop and promote the field, whereof the institute for operations research and the management sciences (INFORMS) today plays a particularly important role.

INFORMS calls operations research simply the 'discipline of applying advanced analytical methods to help make better decisions'. Similarly, Winston (2004) calls it a 'scientific approach to decision making that seeks to best design and operate a system, usually under

conditions requiring the allocation of scarce resources’. According to Render et al. (2008), it is the ‘scientific approach to managerial decision making’. While the scope of such definitions seems to be very wide, a closer look at introductory textbooks in OR reveals that normally, they are restricted to the quantitative modelling approach. Rardin’s (1998) definition specifically reflects this: ‘OR is the study of how to form mathematical models of complex engineering and management problems and how to analyze them to gain insight about possible solutions.’

From reading the above sources, as well as for example Ravindran et al. (1987) and Anderson et al. (1991), it becomes clear that normally, OR is associated with the following main elements:

- The development and analysis of a quantitative model
- The aim to support managerial decision-making
- The thinking in terms of systems

The first two elements have been covered in earlier sections, so focus here is on the third. A *system* is an organized collection of things or components (which may be a subsystem) that does something and exhibits behaviours that none of its components exhibits individually, so-called emergent behaviours (Daellenbach and McNickle 2005). In *systems thinking*, a phenomenon or process is studied in terms of its systemic property and role; the whole is greater than the sum of its parts.

The systems perspective is inherent in OR because it usually develops models of systems and uses them to study the behaviour of systems. While standard OR literature usually pays limited attention to this property, OR can be placed within a larger context of concepts and ideas from systems thinking (see for example Daellenbach and McNickle 2005). In such a context, there are numerous other approaches to problem analysis based on systems thinking – so-called systems methodologies –, for example systems engineering. The traditional quantitative modelling approach is called ‘hard’ OR; others are more qualitative and called ‘problem structuring methods’ (Rosenhead and Mingers 2001b) or ‘soft’ OR (Daellenbach and McNickle 2005). Problem structuring methods overcome some of the limitations of quantitative modelling, which will be discussed in Section 4.14. They would typically be used in situations that contain many qualitative factors difficult to model quantitatively. The System of Systems Methodologies (Flood and Jackson 1991) places ‘hard’ OR and problem structuring methods into a framework according to the assumptions they make about the real world (see Section 4.15).

Thus, for some people, the scope of OR includes also approaches from ‘soft’ OR. This thesis, however, follows the more common understanding that OR is based on quantitative models. Based on these considerations, the following definition of operations research is adopted:

Operations research is the discipline that develops and analyses quantitative models based on systems thinking in order to support managerial decision-making.

The terms *management science* (MS) is sometimes used instead of operations research. The abbreviation OR/MS is also used occasionally. Even though there might be definitional differences for some people, this thesis follows common practice and uses them interchangeably (Render et al. 2008). The terms *quantitative model* and *OR model* will also be used interchangeably.

When a quantitative model is used to support decision-making in a real-world context, this will be called an *OR application* (sometimes *quantitative analysis*). Further details on the process and the context of OR applications will be provided later in this chapter. First, however, a closer look is taken at different types of OR models and techniques because they have fundamentally different properties that affect their use for decision support.

4.5 Basic classifications of OR models

Quantitative models can be classified according to their characteristics. Some of the most basic characteristics and classifications will now briefly be introduced.

- *Descriptive vs. normative model*: A model can be either descriptive or normative. Descriptive models evaluate decision alternatives specified by the user. They can be used to assess the effect on performance (output data) from changes in the decision variables (input data). Thus, in descriptive models, the decision variables are input data. In normative models, also called *prescriptive* models, the decision variables are output data. That is, a solution procedure calculates values for the decision variables that lead to some desired effect. Normative models indicate ‘good’ or ‘optimal’ choices.
- *Deterministic vs. stochastic models*: In deterministic models, uncertainty and randomness are not expressed explicitly. That is, all data is expressed using numeric values. In stochastic models, uncertainty in certain or all parameters is explicitly expressed using probability distributions.
- *Static vs. time-phased vs. dynamic models*: In static models, time is ignored. Only one time period is modelled, but the data for this period often represent averages over several time periods. In time-phased models, several periods and their interactions are represented explicitly. Dynamic models, finally, represent a system as it evolves over time (using a great number of short time periods).

The solution procedures used to solve normative models can fundamentally be grouped into

- *Exact vs. heuristic procedures*: Exact procedures calculate solutions that are ‘optimal’ – that is, no other solution would do better in terms of some specified objective (in the model, not in the real-world). Heuristics are used when exact procedures cannot be used (for example because they would take too much time). Heuristics also calculate solutions that are desirable in terms of some objective (‘good’ solution), but there is no guarantee that these solutions are ‘optimal’.

Several other classifications are frequently used, but since they apply mainly for certain OR subfields, it makes more sense to present them in the next section.

4.6 Main OR subfields/techniques

OR is an umbrella term, covering a wide variety of topics and subfields. Some of them are defined by the type of system they model, for example transportation (Transportation is one of the OR subdisciplines distinguished in the prestigious journal *Operations Research*) or inventory. Other subfields are defined according to the types of models and solution procedures they study and use. In this context, the term *OR technique* is often used instead of OR subfield/subdiscipline. The boundaries between different subfields/techniques are not always clear, and there can be considerable overlap. Terminology is often used inconsistently,

i.e. different people may have in mind different things when using a certain term. This problem will be further discussed in Chapter 5, which also provides a precise characterization of OR techniques used to model logistics flows. Here, a very brief overview of some of the main techniques frequently distinguished in textbooks is provided in order to show the scope of OR. It is mainly based on introductory OR textbooks (Render et al. 2008, Winston 2004, Law and Kelton 2000, Rardin 1998).

Optimization (also called mathematical programming)

In optimization, models represent problem choices as *decision variables* and seek values that maximize or minimize *objective functions* of the decision variables subject to *constraints* on variable values expressing the limits on possible decision choices (Rardin 1998). Optimization models are normative. The following subfields of optimization are often distinguished, according to the model type used:

- Linear programming: In such models, the objective function and the constraints are expressed as *linear functions* of the decision variables, i.e. the decision variables are multiplied by constants and added together.
- Mixed-integer programming: Linear programs where some of the decision variables can only take integer values.
- Integer programming: Linear programs where all the decision variables can only take integer values
- Non-linear programming: Mathematical programs where the objective function or some of the constraints are not linear functions.
- Combinatorial optimization: Optimization models with a finite number of feasible solutions.
- Multiobjective programming (also called goal programming): All the above types of optimization models only have one objective function. In multiobjective programs, there are two or more objective functions that both are to be maximized or minimized.
- Stochastic programming: In stochastic programming, some of the model parameters are expressed by means of probability distributions.

Network models (Graph theory)

Network models represent a system by means of nodes and arcs. Nodes (or vertices) are points, arcs are connections between these points. In many cases, such a representation of a system is useful, and there are many particularly effective solution procedures for network models. Examples include transportation models, shortest-path models and critical path project networks.

Simulation

In its widest understanding, any descriptive model can be considered as a simulation. Thus, a simulation tries different values for the decision variables to see how they affect output measures of performance (output variables). Simulation models can be further divided according to their characteristics (Figure 4-2).

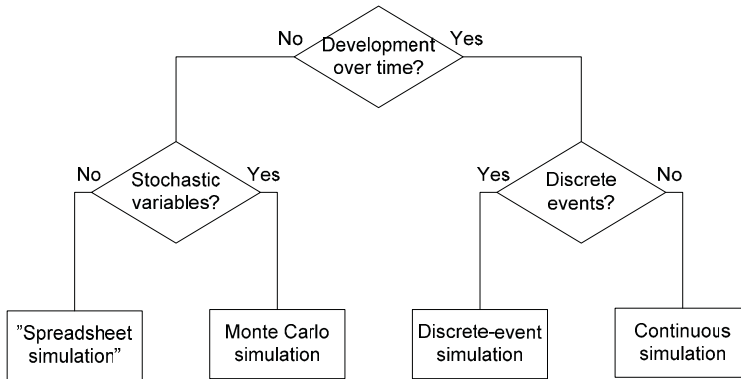


Figure 4-2: The different types of simulation models

The most basic type is the static, deterministic simulation model. In this thesis, such models are called ‘*spreadsheet simulation models*’ because they are often implemented in spreadsheets. A typical example of a ‘spreadsheet’ simulation model would be a listing of costs incurred for various alternative courses of action. ‘Spreadsheet’ simulation models are very common in practice (Power and Sharda 2007), and they are used daily for decision support in most organizations. By definition, they belong to the field of OR. Nevertheless, they are often not explicitly stated as a formal OR technique (Chwif et al. 2002). The reason is probably that they do not require advanced mathematical concepts or techniques. Also in this thesis, focus is on the formal, more advanced techniques usually covered by OR. This is because (1) the usefulness for decision support is in dispute mainly for these techniques, (2) confusion among decision-makers concerns predominantly advanced techniques, and (3) using advanced techniques is particularly resource-consuming (so it is particularly important to be aware of the situations in which they can provide added value). ‘Spreadsheet’ simulation models are only discussed in this thesis where it would have been unnatural not to do so.

If the simulation model is static, but some parameters are stochastic, we have a *Monte Carlo simulation*. Among the dynamic simulation models, a distinction is made between discrete and continuous ones. In *discrete-event simulation*, a system is modelled as it evolves over time by a representation in which the status of the system changes only at separate points in time. In *continuous simulation*, the status changes continuously over time. Note that mostly, the term simulation is used in the context of dynamic simulation (Robinson 2004).

Decision analysis (Decision theory)

Decision analysis includes some general types of models that help analyzing decisions. Often, probabilities are associated with different states of nature, and the value (financial or otherwise) of each alternative outcome is calculated. Decision trees, Bayesian analysis and utility theory belong to this field.

Inventory theory

The purpose of inventory theory is to determine how much inventory to keep to minimize total costs (inventory carrying costs, ordering costs etc.) while satisfying customer service requirements. Inventory models address questions like: When should an order be placed? How much should be ordered?

Queuing theory

Queuing theory studies the behaviour of queues by means of mathematical functions including stochastic variables. Queuing models can be used to calculate queue lengths, waiting times, resource utilization etc. They are often descriptive, but solution procedures are sometimes developed as well, for example to calculate capacity requirements.

Game theory

Game theory deals with decision situations in which two (or more) intelligent opponents with conflicting objectives are trying to outdo one another (Taha 2007).

Dynamic programming

Dynamic programming is a particular type of solution procedure. It is used to solve normative models from various OR subfields, such as network models and inventory models. The basic idea of dynamic programming is to obtain solutions by working backward from the end of the problem toward the beginning, thereby breaking a large problem into a series of smaller problems that are easier to solve. A distinction between deterministic and stochastic dynamic programming is often made.

Markov chains

A Markov chain is a special type of a stochastic process. A stochastic process expresses a system characteristic (for example if a machine is in good, fair or broken-down condition) by means of a random variable and describes mathematically how this variable changes over time. It is used to describe and predict the behaviour of this system characteristic in future time periods. In Markov chains, the speciality is that the probability distribution for the status in a certain time period only depends on the previous time period.

Forecasting

Forecasting models are used to predict future values of input data, such as demand and certain costs. Two important types are time-series methods and causal methods. In the former, future values of a time series are predicted based on past values, assuming the past patterns will continue in the future. In causal methods, past data is used to discover relationships between different factors, such as between the weather and demand for sausages.

In this thesis, a small restriction in scope is made: Focus is on OR models of *material/information flows*. The models developed by decision analysis are of a different nature, and they therefore fall outside scope. This is just a minor restriction because the core modelling area of OR in operations management is logistics flows (Murphy 2001). Note also that forecasting models lie outside scope because forecasting is considered part of marketing/sales (see Figure 3-2); it provides important input data for logistics decision-making, but is not considered as a logistics activity itself.

This and the previous section have given insights into the different model types and subfields constituting the field of OR. They exhibit rather different properties both from a theoretical and practical decision support perspective, and therefore need to be studied separately. This will be done in subsequent chapters. The remainder of the present chapter concentrates on issues and properties that are common for all types of OR models.

4.7 OR from an IT perspective

The development of OR has only been possible thanks to the progress of computer technology. Most models involve such a large number of variables and mathematical relationships that manual calculation would not be possible in practice. The rapidly decreasing computer processing times over the past decades have allowed the development of models with constantly more data, variables and relationships. More and more what-if analyses and sensitivity analyses have become possible, as well as the use of ever-improved solution procedures. Today, computers can do thousands of calculations within seconds. In addition, computers can speed up actual modelling. For example, icons, symbols and formulae can be stored, edited and accessed in libraries, thereby avoiding a lot of repetitive work. Thus, computers play a key role in the development and use of quantitative models.

Transactional vs. analytical IT

Shapiro (2001) distinguishes between two fundamental types of IT: Transactional IT and analytical IT. Transactional IT acquires, processes and communicates data. The data may come from internal sources, such as a shop floor control system, or from customers and other stakeholders. Transactional IT also summarizes and visualizes data and develops reports. A dashboard visualizing key performance indicators, for example, would be a typical, advanced application of transactional IT.

Analytical IT is concerned with the development and use of quantitative models for decision support, the way it has been described earlier in this chapter. Shapiro (2001) emphasizes the importance of distinguishing between these two types of IT, and of making use of both. Table 4-1 contrasts them across a number of aspects (Shapiro 2001). Such comparisons are useful to understand and exploit the opportunities of IT, both transactional and analytical.

Table 4-1: Comparing transactional and analytical IT (based on Shapiro 2001)

	Transactional IT	Analytical IT
Time frame addressed	Past and present	Future
Purpose	Communication	Forecasting and decision-making
Business scope	Myopic [operational]	Hierarchical [from strategic all the way to operational decision-making]
Nature of databases	Raw and lightly transformed objective data	Raw, moderately and heavily transformed data that is both objective and judgmental
Response time for queries	Real-time	Real-time and batch processing
Implications for business process redesign	Substitute for or eliminate inefficient human effort	Coordinate overlapping managerial decisions

While the majority of the table is straightforward, two items can require some explanation. The fact that analytical IT includes judgmental data may appear surprising in light of the objectivity of the mathematical models used. It refers to input data that cannot be measured, for example the desired product availability when calculating safety stock requirements. Such

data is necessarily judgmental. Transactional IT is characterized as myopic because it is concerned with current transactions and the compilation of histories based on them (Shapiro 2001). While such data provides important input for decision-making at all planning horizons, transactional IT does not by itself use them to make predictions about the future or address/analyze any particular decisions (the purpose of analytical IT).

IT systems may also be characterized according to their goals. In the context of supply chain management, Simchi-Levi et al. (2008) suggest four goals, whereof the following is achieved by analytical IT: ‘Analyze, plan activities, and make trade-offs based on information from the entire supply chain’.

Model-driven decision support systems

One IT-based research area evolves around the concept of a *decision support system* (often abbreviated *DSS*). A decision support system is a computerized system that provides decision support. This broad definition is based on Power (2001). Turban and Aronson (2001) review narrower definitions.

Essentially, a decision support system consists of four components (Turban et al. 2007, Sprague and Carlson 1982):

- The *data management subsystem* contains relevant data for the situation analysed, for example, sales data, costs, times or distances.
- The *model management subsystem* includes quantitative models that provide the system’s analytical capabilities.
- The *knowledge-based management subsystem* contains knowledge that can augment the decision-maker’s own. In a decision support systems supporting plant location, for example, it may provide information about important qualitative factors to be considered, such as infrastructural, political and educational issues.
- The *user interface subsystem* is responsible for communication between the decision support system and the user. The user interacts with the computer via an action language. This language can be formal or close to natural language and it can contain graphical capabilities such as buttons, windows, drag-and-drop icons etc.

Figure 4-3 illustrates these components.

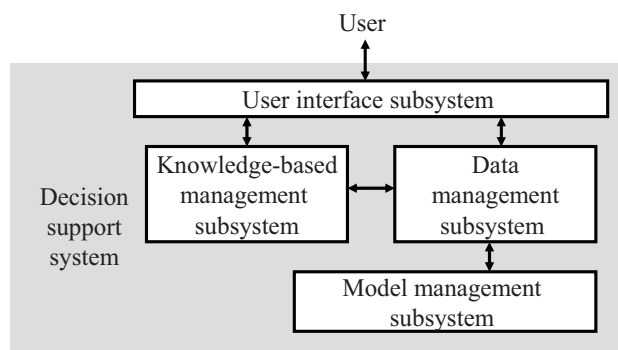


Figure 4-3: The four subsystems of a decision support system (based on Turban et al. 2007)

While most decision support systems contain some kind of data management subsystem and user interface subsystem, the model management subsystem and the knowledge-based management subsystem may not be present. More generally, the importance and degree of sophistication of each of these four subsystems varies considerably between different types of decision support systems.

These differences in the importance of the various subsystems can be used to classify decision support systems. Several authors do this, including Power (2002), Holsapple and Whinston (1996) and Alter (1980). Power's classification (2002) is comprehensive, useful and has a manageable number of categories. It distinguishes between the following five generic types of decision support systems:

- *Data-driven decision support systems*: In such systems, the data management subsystem is prevalent. They give access to and allow manipulation of large databases. Examples include data warehouse systems, Executive Information Systems (EIS), and Business Intelligence (BI) systems.
- *Model-driven decision support systems* (also called *model-based decision support systems*): At the core of such systems are quantitative models. These models are accessed and used to carry out different analyses requested by the user. Model-driven decision support systems are closely related to OR. In most cases, OR models are implemented in software systems, resulting into such model-driven decision support system. Very large databases are not usually needed for model-driven decision support systems, but data for a specific analysis may need to be extracted from a large database (Power 2002). Power and Sharda (2007) provide a recent overview of concepts and research directions related to model-driven decision support systems.
- *Knowledge-driven decision support systems*: Sometimes called Suggestion decision support systems or Management Expert Systems, these systems contain computerized 'expertise' (knowledge) about a particular domain, as well as skills about how to solve related problems. They consist of guidelines, checklists, rules of thumb etc. See Sunduck et al. (1990) for an example of an expert system in plant location. A computerized, interactive version of the guidelines presented in Chapter 9 would also be a knowledge-driven decision support system.
- *Document-driven decision support systems*: These systems help organize, retrieve and analyse documents and web pages. Examples of such documents include policies, product specifications, minutes of meetings etc. Such systems are also called Knowledge Management Systems. Product lifecycle management (PLM) systems constitute a recent example of this type of decision support systems.
- *Communications-driven decision support systems*: This category includes communication and collaboration technologies. Examples include so-called Group decision support systems (systems that support decision-makers working together as a group), video conferencing tools, bulletin boards and e-mail.

Many decision support systems do not fall neatly into one of the above categories; such systems are called *hybrid* systems. Hybrid systems provide strong capabilities in several categories. On-Line Analytical Processing (OLAP) systems, for example, are sometimes linked to large databases and allow modelling as well as data retrieval and summarization.

Thus, the scope of the present thesis could be defined as model-driven decision support systems because usually, the physical product resulting from an OR application is such a system. Once it is implemented, it can be used repeatedly to support the type of problem situations it is intended for. For irregular, strategic problem situations, this normally requires OR professionals to make necessary modifications in the model/system. For regular, operational/tactical problem situations, easy-to-use user interfaces are often developed, so that decision-makers do not depend on OR professionals and can use the system themselves.

Standard software systems

In order to simplify the process of using OR for decision support, software vendors have implemented some OR models in standard (i.e. not company-specific) software systems. Even though such systems require some customisation, it is normally limited. One of the most successful examples is the use of inventory-theoretical models in inventory management systems (also called replenishment systems or purchasing systems). In these systems, models often calculate safety stock requirements and replenishment quantities.

A second type of standard software systems using OR techniques is called *APS systems*. APS means *Advanced Planning System* or *Advanced Planning and Scheduling*. Although there is no generally agreed-upon definition of APS systems, such systems are meant to remedy some of the deficiencies of Enterprise Resource Planning (ERP) systems as planning tools. APS systems are add-ons to ERP systems. As opposed to traditional ERP systems, they can produce plans that are capacity-feasible (using optimization). Also, they integrate various planning functions using *hierarchical planning*. In hierarchical planning, different modules are called upon for strategic, tactical and operational planning. The strategic modules provide input and constraints for the tactical modules, which in turn provide input and constraints for the operational modules (see Stadtler 2005c).

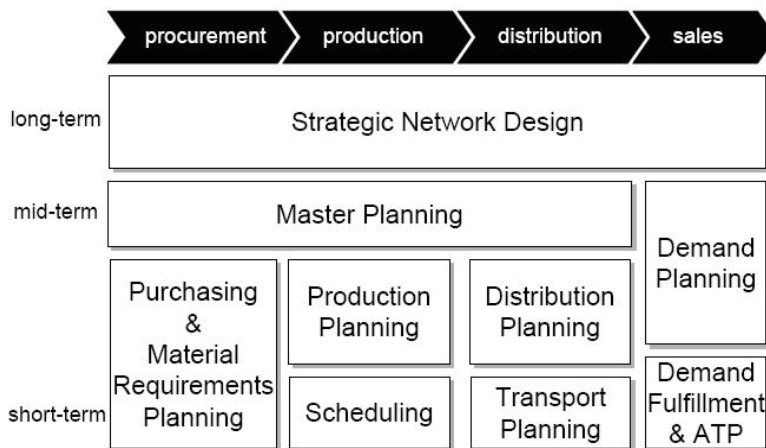


Figure 4-4: The typical modular structure of APS systems (Meyr et al. 2005)

Figure 4-4 shows the typical modular structure of APS systems (Meyr et al. 2005). It reflects the Supply Chain Planning Matrix presented in Subsection 3.5.3, in the sense that each module support a different area in the matrix. Each module has its own quantitative models,

supporting certain specific tasks (but not all of them) within its area of the matrix. For many more details on APS systems, see Stadtler and Kilger (2005).

When introduced in the early nineties, APS systems attracted a lot of top management attention since software vendors claimed they sold standard software, just like ERP systems. They claimed huge profits with company-wide implementation of APS systems. In 2001, AMR Research concluded that these promises were not realised and that APS system implementations were restricted to stand-alone modules instead of integrated APS suites (De Kok and Graves 2003). De Kok and Graves (2003) explain this failure by emphasizing that a typical business' peculiarities require much customization and development of tailor-made solutions. As far as strategic APS modules are concerned, their limited success is further discussed in Subsection 9.7.1. Thus, while certain types of OR applications can be standardized, many of them seem to require considerable customization in order to respond to the needs of each particular situation.

This section's conclusion is that, from an IT perspective, OR applications develop model-driven decision support systems and use them for decision support. This thesis' title, issue and research objectives could therefore also have been expressed in terms of model-driven decision support systems: 'Applicability of model-driven decision support systems in manufacturing logistics'. So, while this thesis takes an OR perspective, its results are also relevant within the IT context of model-driven decision support systems.

4.8 The process of an OR application

The process of using quantitative models for decision support can be described in more detail by means of a series of steps. Figure 4-5 shows the researcher's version of this process, based on Render et al. (2008) and Law and Kelton (2000).

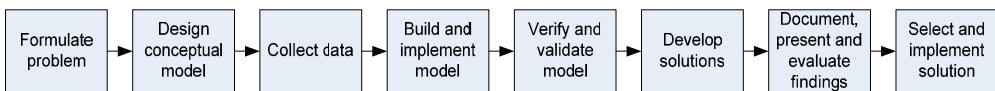


Figure 4-5: The different steps of a typical OR application

Formulate problem

First, management needs to define as precisely as possible the problem to be solved, and communicate it to potential model analysts. This is often a difficult task because the real problem is hidden behind symptoms, because of differing perspectives and interests, because there are normally several reasons behind an unsatisfactory situation, etc. For example, the cause of late deliveries may be bad transportation management, poor inventory management, problems in production or a combination of these. Daellenback and McNickle (2005) elaborate on this step and present useful tools and methods supporting it.

Design conceptual model

In this step, a conceptual model is developed, specifying the aspects to be included in the quantitative model, as well as required input data and desired output data. The data system to be used is selected, time/resource requirements specified and a time plan established. This is carried out in close collaboration between the managers and the model analysts.

Collect data

Relevant data is collected from various sources, including company databases, reports and documents, as well as by means of interviews, inspection and direct measurement. Data collection is often the most time-consuming step of the entire analysis because data is frequently not available, not accurate or not updated. Company employees may not provide the necessary information, be it because they do not know it, they do not want to provide it, or they simply do not prioritize the task. Good data quality is necessary in order for the results to be meaningful. The opposite situation is often described as ‘garbage in, garbage out’ (Render et al. 2008).

Build and implement model

This phase involves the actual building of the model in the software system. Some models can be implemented in spreadsheets, others require more specific and advanced tools. Some years ago, most models had to be implemented using languages similar to computer programming languages; more recently, however, user-friendly systems with graphical interfaces and drag-and-drop-type functionalities have become more and more common.

Verify and validate model

Model *verification* means ‘debugging’ the model, i.e. making sure it contains no programming errors. It refers to the question ‘Does the model do what I want it to do?’ Model *validation* assures that the model is an accurate enough representation of the real situation; ‘Is the model realistic enough to give meaningful results?’ While verification is usually carried out by the modeller alone, validation is done in collaboration with those who know the real system, such as managers and technical personnel. Robinson (2004) presents techniques for model validation.

Develop solutions

The model is now ready to be used for analysis. Various solution procedures are used to identify desired (‘good’ or ‘optimal’) solutions. The solutions are ‘good’ or ‘optimal’ in the model world, i.e. given the assumptions and simplifications made in the model and its data. What-if analysis and sensitivity analysis are carried out. Strengths and weaknesses of different solutions can be assessed, providing a greater understanding of the model and thus, to a certain degree, of the real system.

Document, present and evaluate findings

The understanding gained from the model is communicated to the managers who need to evaluate it. A report summarizes model assumptions, input data and results. Oral presentation often focuses on assumptions and model validity in order to increase model credibility. Visualizations and animations can support this communication and validation. Often, the decision-makers ask for additional model analysis (as in the anecdote in Section 4.3), which requires a repetition of previous steps.

Select and implement solution

Finally, a decision is taken by selecting a solution. As explained, model results provide the decision-maker with a better understanding of the situation, but more qualitative aspects will normally also affect the final decision. The selected solution needs then to be implemented in

the company, which requires consensus of involved parties and a certain trust into quantitative modelling. Managers may resist the solution, which is not uncommon (Render et al. 2008). In this case, the entire study can have had very limited value.

These steps are carried out in most quantitative analyses, but they can overlap and their role and importance can vary considerably. Data collection, for example, is often necessary at several instances, from problem definition all the way to the selection and implementation of a solution. Moreover, the steps do not form a linear process, but often involve several loops, for example when model validation reveals a need to redesign the conceptual model. A distinction can also be made between strategic and more tactical/operational models. In a strategic analysis, most steps would normally be carried out carefully to answer a particular issue. For more tactical/operational decision-making, for example order quantities, the models are typically made available for the managers by means of easy-to-use interfaces. Little or no modelling would normally be required after initial implementation, data collection is often automated and findings are more directly used in decision-making.

For clarity, it must be mentioned that the term ‘implementation’ is used with two different meanings, both here and in literature more generally. *Model implementation* is the programming of a model into a computer system, which will then be used to support decision-making. *Solution implementation* refers to the actions or changes carried out by the company after a final decision is taken.

In addition to the process, the context also needs to be addressed for a holistic understanding of an OR application.

4.9 The context of an OR application

The *context* of using a quantitative model for decision support can be structured into three related parts (adapted from Mingers 2001b):

- The *problem situation*, given by the real-world situation of concern
- The *application system*, consisting of the people engaged with the problem situation
- The *intellectual resources*, i.e. the modelling techniques and software systems

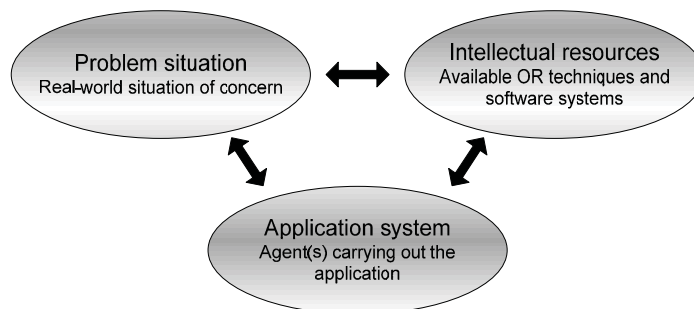


Figure 4-6: The context of an OR application (adapted from Mingers 2001b)

Figure 4-6 illustrates these three parts. The *problem situation* consists of one or several *decisions* to be taken, as well as the *characteristics* of the real-world system. For example,

scheduling production in a high-variety environment is a problem situation. The scheduling of production is the decision; high-variety environment is a system characteristic. Table 3-3 on page 47 lists numerous system characteristics. The Supply Chain Planning Matrix on page 54, on the other hand, provides a framework of decisions. The scope of this thesis is problem situations in manufacturing logistics.

The application system consists of all the people concerned with the problem situation and possibly being ordinarily part of it. It includes the agents carrying out the quantitative analysis. Usually, it is collaboration between managers and modellers. Managers include the actual decision-makers as well as other key staff knowing the problem situation. They are mainly responsible for problem formulation, data collection, model validation, result evaluation as well as selecting and implementing a solution. Modellers, on the other hand, conceptualize, build, implement, verify and analyze the models, and they document and present findings.

The intellectual resources, finally, consist of the tools and techniques available to the modeller, i.e. the entire body of knowledge about quantitative models for management. As will be explained later in this chapter, this body has grown explosively over the past decades and now consists of a plethora of models, techniques and solution procedures. The intellectual resources also include the data systems available for model implementation, such as spreadsheets and the numerous other more or less specialized systems. There are also methods for tasks such as problem formulation and model validation, which are typically of a more qualitative nature.

The most important aspect of this section is the definition of the term ‘problem situation’, because a key issue of this thesis is the link between problem situations and OR techniques.

4.10 The gap between OR theory and OR practice

By now, a general understanding of what OR is and how it supports decision-making has been achieved. The scope is now narrowed and directed towards the specific issue addressed in this thesis.

The definition of OR implies that it is something practical, aiming to support problem solving in the real world. Nevertheless, as the discipline matured, a considerable body of ‘theoretical’ (i.e. unempirical, not based on practical experience) knowledge has been established. This body includes thousands of models as well as solution procedures, each with different properties and modelling different aspects. Many researchers aim to expand this body of ‘theoretical’ knowledge, without necessarily applying their results in a practical real-world problem situation. For some, this body of knowledge even *is* OR (Ravindran et al. 1987). A lot of research literature therefore also focuses on the development of models and solution algorithms, often without using them for decision support in practice (Pidd and Dunning-Lewis 2001). The intention is that other operations researchers will use it in practice whenever appropriate. This has eventually led to a distinction between OR professionals doing ‘theoretical’ research, and *OR practitioners*, i.e. OR professionals who actually apply models in real-world situations. It also explains the term *OR application*, which at first may seem almost tautological, since the common definition of OR implies that it is applied.

Basically, there is nothing wrong with such a distinction between theory and practice. However, while academia continues to publish papers on new models and new and faster solution procedures, literature on application of this knowledge in the real world is much

more limited. This has led to the famous ‘gap between theory and practice’, which has been extensively discussed (Hooker 2007, Meredith 2001, Corbett and van Wassenhove 1993).

Some of this gap is probably due to the difficulty of publishing papers on real-world applications. The models used may not be novel enough, or the benefitting companies do not want competitors to know them (Tilanus 1985). Most research journal in the field of OR focus on theoretical work. However, the gap also suggests that many models and solutions have never been used in practice. For many people, this is what the famous gap refers to (for example Gershwin 1994). It raises the question of the models’ *applicability*, i.e. if they actually *can* provide useful decision support. It concerns the scope of OR as an approach to support decision-making. Many models developed in theory may address practically relevant issues; however, they may not work in practice because they ignore some key aspects or make certain unrealistic assumptions. This is the view taken by Russell Ackoff and the advocates of ‘soft OR’. They argue that the assumptions made by traditional, quantitative OR are violated in most real-world problem situations. Ackoff has written some famous articles about this limitation, among them ‘The future of operational research is past’ (Ackoff 1979a) and ‘OR: A post mortem’ (Ackoff 1987). The diabolo model in Figure 4-7, which is inspired by Tilanus (1985), illustrates this situation. There is a large body of OR models and solution procedures in the literature (OR ‘theory’). There are also a great number of real-world problem situations. However, only a limited part of the OR body of knowledge works in practice, and only a limited part of all real-world problem situations are suitable for OR support (OR ‘practice’).

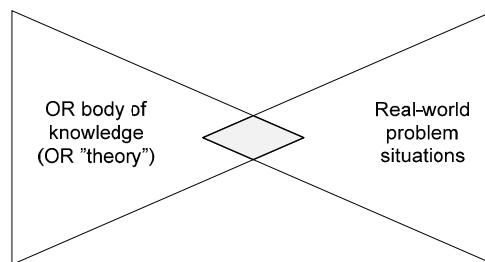


Figure 4-7: The diabolo model illustrates the gap between OR ‘theory’ and OR ‘practice’. This gap suggests that OR practice (i.e. OR applications) is limited to the grey area in the centre of the diabolo.

The stance taken in this thesis is that OR has strengths and limitations. In certain circumstances, it works well, in others, other approaches work better. In order to exploit the potential of OR, it is therefore important to understand the circumstances in which it works well, i.e. in which it is applicable. Gaining and communicating this understanding for manufacturing logistics is the purpose of the present research.

4.11 Factors affecting the applicability of OR techniques

The previous section has introduced the gap between existing OR theory and what has actually been used for decision support. OR has been applied successfully in some circumstances, but is not a panacea that works in all cases. So it is natural to ask in which circumstances it is appropriate to use OR. In other words, in which contexts can OR provide useful decision support?

The same question can be asked at a lower level, separately for the different techniques within OR. Different OR techniques have different properties, different strengths and limitations, and

they provide decision support in different ways. As a consequence, each works well in some circumstances, but may be less relevant in others.

www.thefreedictionary.com defines the term applicability as ‘relevance by virtue of being applicable to the matter at hand’. It defines ‘applicable’ as ‘relevant’ or ‘appropriate’. The applicability of OR and its techniques to support decision-making is thus its relevance by virtue of being appropriate for decision support. That is, their appropriateness to provide decision support. The following definition is adopted:

The applicability of OR and its techniques to support decision-making in a certain context is the degree to which they can provide useful decision support.

For simplicity, the expression ‘applicability of OR techniques’ or simply ‘OR applicability’ will be used instead of the more precise ‘applicability of OR and its techniques to support decision-making in a certain context’. Understanding the applicability of OR techniques means understanding in which contexts they work well. Several authorities have stressed that this is not obvious (Murphy 2005a, Flood and Jackson 1991). It is, however, critical for decision-makers, who struggle to select appropriate approaches and techniques for support. It is equally relevant for OR professionals in order to find promising application areas of their techniques. Recognizing where the different OR techniques possess added value is an important prerequisite for successful OR application. This has been emphasized in particular by industrial consultants using OR, such as Mayo and Wichmann (2003) and Fortuin and Zijlstra (2000). Moreover, lacking understanding of what OR does and what it can be used for, has been recognized repeatedly as an important reason why OR is not used in practice more often (Hooker 2007, Murphy 2005c).

The applicability of OR in a certain context depends on numerous contextual factors. Available time and resources are crucial factors, as well as available expertise, motivation and the level of technological awareness in the involved organizations. Mingers (2001b) uses the three parts of the context of an OR application (see Section 4.9), more specifically the relations between them, in order to structure such factors. He proposes critical questions agents (the people who are supposed to provide decision support) should consider when assessing the appropriateness of different systems methodologies, such as OR. Figure 4-8 shows examples of such questions, which are clearly relevant when assessing the applicability of OR in a given context.

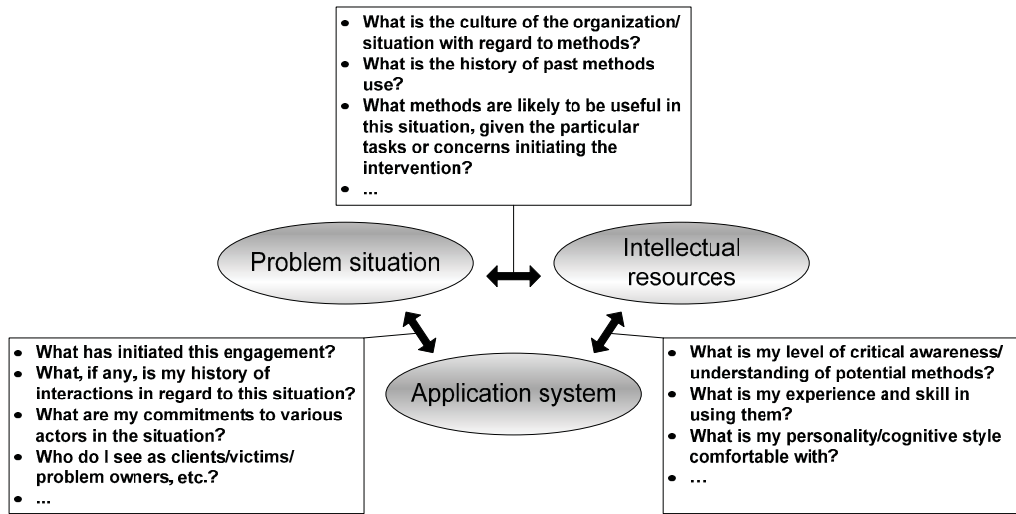


Figure 4-8: Examples of questions to be asked when assessing the appropriateness of OR in a given context (Mingers 2001b)

Some literature addressing the applicability of OR takes a slightly different perspective and studies *success factors* of OR applications. Which contextual factors make an OR application successful? Ravindran et al. (1987), for example, concentrate on the model (intellectual resources):

- 1) Do not build a complicated model when a simple one will suffice
- 2) Beware of moulding the problem to fit the technique
- 3) The deduction phase of modelling [drawing conclusions from the model] must be conducted rigorously
- 4) Models should be validated prior to implementation
- 5) A model should never be taken too literally
- 6) A model should neither be pressed to do, nor criticized for failing to do, that for which it was never intended
- 7) Beware of overselling a model
- 8) Some of the primary benefits of modelling are associated with the process of developing the model
- 9) A model cannot be any better than the information that goes into it
- 10) Models cannot replace decision-makers

Murphy (1998) also discusses how to make OR work, but focuses less on the model and more on the behaviour of the OR practitioner (application system), especially towards the client. Recently, he provided a list of skills OR practitioners need to have (Murphy 2005a):

- 1) Knowledge of mathematics
- 2) Practical knowledge of tools, programming languages and computing
- 3) Cognitive skills for mapping problems into models
- 4) Problem-abstraction skills for translating symptoms of a problem into a meaningful definition of the problem

- 5) Management and team skills for organizing and completing projects on time and on budget
- 6) Communication skills and the ability to understand customer needs and wants
- 7) Marketing and strategic-positioning skills that expand the field into new customer classes and areas and develop business, and the ability to recognize what environments are conducive to the successful implementation of OR
- 8) Relationship management skills for building a social network of contacts on the technology and business sides of [OR] practice.

Items 1 and 2 are typically taught in OR courses at universities, items 5 to 8 have been covered in general terms in the literature on organizational behaviour, marketing and business strategy (Murphy 2005a). Items 3 and 4 thus seem to be those who have received least attention. The researcher considers the present thesis as falling mainly into the domain of item 3.

Wagner (1969) also focuses on the people involved in an OR application and covers the following issues as important success factors:

- Managerial guidance and participation
- Project planning and control
- Credibility [of the model and modeller]
- Responsive and responsible implementation
- [Data] Systems design

This is not the most recent publication, but the factors it discusses certainly still apply. The reasons for success or failure of OR applications have also been investigated in several surveys. Abdel-Malek et al. (1999), for example, surveyed OR practitioners and found the results shown in Table 4-2. Jeffrey and Seaton (1995) and Tilanus (1985) made similar findings, surveying OR practitioners and OR applications, respectively.

Table 4-2: Factors affecting the success and failure of OR applications (Abdel-Malek et al. 1999)

<i>Factors affecting project success</i>	<i>Factors leading to project failure</i>
Management support/involvement	Too technical/abstract approach
Verifiable and useful results	Customer not sold on the project
Well organized/communicated/presented	Poor communication
Economic benefits/business results	Poor problem definition/planning
Understanding true spirit of request	Lack of professional competence
User support/involvement	Over budget, not timely
Timeliness	

Several of the above studies put considerable emphasis on people (application system) and model (intellectual resources). Simchi-Levi et al. (2008) focuses on the problem situation when listing factors affecting the choice of decision support system:

- The type of problem being considered

- The required accuracy of the solution
- Problem complexity
- The number and type of quantifiable output measures
- The required speed of the decision support system
- The number of objectives or goals of the decision-maker

This review shows the breadth of factors that affect the success or failure of an OR application. Nevertheless, there is generally agreement that a crucial factor determining the applicability of OR techniques is the problem situation. Rosenhead and Mingers (2001a), for example, ask where the line is drawn between problem situations that can benefit from an OR-based analysis, and those that fall outside the scope of OR. Murphy (2005a) emphasizes that ‘the potential for success with OR ... depends on the nature of the problem’. Concentrating on the field of material planning and control, Olhager and Rapp (1995) stress the importance of understanding the problem situations for which models are supposed to be used. Several empirical studies have also shown the importance of using OR techniques only when they fit a given problem situation, including the ones carried out by Abdel-Malek et al. (1999), Jeffrey and Seaton (1995) and Tilanus (1985). These and other studies have suggested that a mismatch between problem situation and technique is a frequent reason for failure of OR applications in practice. Abdel-Malek et al. (1999), for example, conclude that ‘the tendency of OR practitioners to superimpose inappropriate theoretical structures upon business problems, one of Ackoff’s reasons for pessimism, continues to be a major inhibitor to successful application.’

At the end of this chapter, research attempting to define the problem situations OR is suitable for will therefore be reviewed. Moreover, much of this thesis focuses on the link between problem situation and OR technique applicability. First, however, the process of selecting techniques is taken a closer look at, as this is where knowledge on their applicability comes into play.

4.12 OR Technique selection

The previous section discussed the factors affecting the applicability of OR techniques and it highlighted the importance of selecting OR techniques that fit the given problem situation. This is often not easy. Each technique has its strengths and limitations, and several techniques may provide useful insights, each in its own way. Limited budget however often necessitates the selection of one technique. This section discusses the relevance of technique selection from an operations management perspective, and it discusses literature and current practice related to technique selection.

While technique selection is of course a central activity within the field of OR, this thesis treats it from an operations management perspective. In such a perspective, technique selection is mainly interesting at a *high* level (rather than detailed), where techniques differ in the following fundamental ways:

- (a) Paradigmatic differences. They have fundamentally different world views, i.e. ‘glasses’ through which the real-world system is viewed. Different aspects are emphasized, different ignored, and decision-making is supported in different ways.

- (b) They are practised by different OR professionals. OR professionals often need to specialize in one or a few techniques, having only superficial knowledge and experience in other OR techniques. This is a natural trend as the body of knowledge in a field grows bigger.
- (c) They are implemented in different types of software systems and marketed by different software vendors.

At a level with such differences, technique choice is relevant for decision-makers because it fundamentally affects how decision-making will be supported, as well as who will carry out the analysis and what software system might have to be purchased. At this level, they therefore need to have an understanding of OR techniques, even though they will not normally develop models themselves.

Also, at this level, technique selection is particularly difficult. One can observe confusion among decision-makers and even OR professionals about the different techniques' range of application. The different techniques are often seen as competing and sometimes considered as different 'religions'. To a certain degree, different techniques may be compared to Kuhn's concept of paradigms (1970), where different perspectives or 'world-views' demonstrate a flavour of incommensurability, i.e. they cannot easily be compared and ranked according to suitability criteria. Technique selection is also frequently regarded as an art (Brooks and Tobias 1996), which can only be mastered by gradual acquisition of experience. Nevertheless, the remainder of this thesis demonstrates that much can be said about the applicability of different OR techniques in a given context.

Banerjee and Basu (1993) note that model use appears to be carried out in a rather ad hoc way. Empirical evidence has shown that OR professionals do not use any formal process to analyse the options available, although detailed consultations can take place before a technique is finally adopted (Jeffrey and Seaton 1995). They are aware of the limitations of the technique they use and are concerned to communicate them to decision-makers and clients, but they often do not explicitly reflect on or articulate their methodological choices (Munro and Mingers 2002, Jeffrey and Seaton 1995). Given the importance of selecting appropriate techniques, such practices can be dangerous.

In particular, they entail the danger that the advocates of a certain technique overestimate the potential of their own technique and recommend it too quickly. Woolsey (2006a, 2006b), Daellenbach and McNickle (2005), and Brown (2005) all observed this. Mayo and Wichmann (2003) called it the propensity for modellers to view every problem through the lens of the technique with which they are most familiar. As stated above, the survey by Abdel-Malek (1999) also indicated a tendency of OR professionals to superimpose inappropriate theoretical structures upon business problems. The danger is that unsuitable techniques are used and one ends up with an elegant analysis of the wrong problem (Daellenbach and McNickle 2005).

Discussions between advocates of different techniques abound. For example, discussion and even argument about the appropriateness of simulation as opposed to optimization for logistics and supply chain problems has raged for decades (Powell 2005, Riddalls et al. 2000, Mentzer 1989). Literature on the applicability of each technique tends to be made from the biased perspective of each technique's experts, often emphasizing its advantages, but paying less attention to its weaknesses and the advantages of alternative techniques (Mentzer 1989, Meadows and Robinson 1985). For instance, [discrete-event] simulation is stated to be often the only means for accurately predicting performance if the systems modelled are subject to

significant levels of variability (Robinson 2004), and optimization is declared to be the only analytical tool capable of fully evaluating large, numerical databases to identify optimal, or demonstrably good, plans (Shapiro 2001). While these statements can provide some indications of the appropriateness of different techniques, they are often of limited practical support for decision-makers, who typically face systems that simultaneously require good plans, are data-intensive, and are highly variable. The real question is in which contexts each technique's strengths are most valuable.

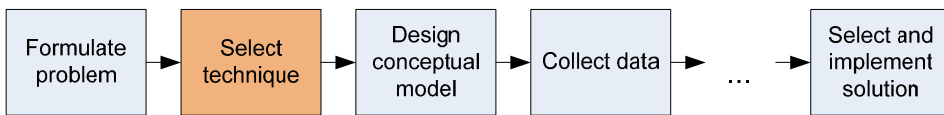


Figure 4-9: Revised process of an OR application, with an additional step 'Select technique'

In conclusion, selecting appropriate OR techniques is an important and difficult step in a (potential) OR application, requiring close involvement of the decision-makers. A revised process model is therefore suggested, where technique selection constitutes a separate step after problem formulation and before conceptual model design (Figure 4-9). This step is carried out in collaboration between the decision-makers and OR professionals who – ideally – have knowledge and experience in several OR techniques. The outcome from this step will be either a selected technique, or the conclusion that no OR techniques is appropriate. In the latter case, the subsequent steps of an OR application are not carried out and alternative approaches to decision support are considered. If a certain OR technique is deemed appropriate and selected, the selection is decisive for which OR practitioner is to carry out the OR application, which software system to use, time requirements etc. The present thesis aims to support the 'Select technique' step for decisions in manufacturing logistics.

Strengths and limitations of OR in general will be presented next, as understanding them is crucial for understanding the applicability of OR.

4.13 Strengths of OR

At the beginning of this chapter, some general benefits of models have been outlined. What follows is a more detailed presentation of the benefits of *quantitative* models. It is based on various authors' claims, including Turban et al. (2007), Williams (1999) and Melnyk and Denzler (1996):

- Experimenting with the model facilitates understanding of the real system and its behaviour, which may be very complex. By means of what-if and sensitivity analysis, a better understanding of the effects and risks of different alternative scenarios/solutions is achieved. Experimenting with models is easier, cheaper, faster and far less risky than making changes in the real world.
- Models can provide a common representation of a situation, facilitating communication, reducing mutual misunderstanding and providing a common base for discussions. This way, models facilitate collaborative development and evaluation of ideas.

- For some models, such as all optimization models, procedures have been developed that calculate solutions with desired properties (normative models). This is particularly useful when there are a large number of possible solutions. Such procedures can quickly assess thousands of alternative solutions and identify the ones best meeting certain requirements, such as low costs or high profit.
- Models can be used to estimate the savings to be expected from a suggested improvement. Such a quantitative estimation can be used to prioritize improvement efforts and to convince senior management. ‘Without an adequate analysis tool, opportunities for change might be lost for want of credible argument.’ (Davis 1993)
- The actual exercise of building a model forces people to think through issues that otherwise may not have been considered. Previously unapparent relationships can be revealed. This results in a greater understanding of the system being modelled.

In a survey of OR practitioners, the following advantages from the use of OR were stated most frequently (Jeffrey and Seaton 1995):

- Provides a broader understanding of often complex problems
- Develops a scientific approach based on quantification
- Allows a structured approach to problem analysis
- Constitutes an independent/objective analysis
- Resultant decisions made/seem to be made on a rational basis
- Ensures cost effective decisions/effective resource allocation

Most of these answers emphasise the use of a structured and objective approach to reasoning and problem analysis. This can be regarded as a core strength of OR. It assumes, however, that structured/objective reasoning leads to desirable decisions and benefits for the organization (Jeffrey and Seaton 1995). While this assumption is widely accepted (Jeffrey and Seaton 1995), it may actually be considered as a limitation of OR because it ignores factors such as experience and intuition. Stenfors et al. (2007), for example, found that some executives perceived more structured work as increased bureaucracy.

In general, however, its structured and rational reasoning makes OR a powerful approach to increasing the managers’ rationality and supporting their decision-making.

4.14 Limitations of OR

The limitations of OR are often not stated clearly in traditional OR textbooks, but they can be found in texts taking a larger problem solving perspective, for example Daellenbach and McNickle (2005) and Rosenhead and Mingers (2001b). Russell Ackoff has also been a central figure in discussing the weaknesses of OR (see for example Ackoff 1979a). The present section draws upon such studies.

Models express the relationships in real-world systems by means of mathematical and logical expressions. The behaviour of the models’ components is completely specified during model development, very much like mechanical machines or computer software. The real-life systems decision-makers normally deal with are not machines, however, but contain

individuals, groups and even societies (cultures). Such systems do not exhibit machine-like properties. To some extent, personal and social factors affect their behaviour, such as emotions, feelings, personal ambitions, power, pain and the like. Such behavioural factors are difficult to express by quantitative rules or formulae. OR has therefore been characterized as 'contextually naïve' (Ackoff 1979b).

For illustration of this fact in the context of manufacturing systems, consider Hopp and Spearman's (2001) factory physics principles. They are a collection of laws that describe the underlying behaviour of manufacturing systems. While some of these laws are quantitative, there are also a good deal more qualitative ones. The following examples describe some behaviour of people:

- Law (Individuality): *People are different*
- Law (Burnout): *People get burned out*

Such factors can play an important role in the behaviour of the system, but they cannot easily be expressed by means of a formula or some other quantitative expression.

Modellers are therefore required to make simplifying assumptions and omit factors that are difficult to quantify. The danger is that the models do not represent the real system accurately, or do not address the decision-maker's actual problem situation. In other words, simplifying assumptions can lead to analyses that are technically sound, but disregard key knowledge, make unrealistic assumptions and answer the wrong questions.

OR results can therefore be misused or interpreted erroneously. If the decision-makers agree with the results, they uncritically use them as a scientific confirmation of what they 'knew' from before. Otherwise, they stress the model's weaknesses and ignore its results. More generally, there is the danger that quantifiable aspects are overemphasized and qualitative factors not given enough weight. Attention can be shifted away from reality and limited to the factors and relationships taken into account by the model. Fuglseth and Grønhaug (2003) investigate and show this empirically.

The simplifying assumptions OR needs to make can be considered as its key weakness. A number of additional weaknesses can be named:

- OR often uses mathematical concepts and techniques that are too complex to be understood by people without formal OR education. OR models therefore frequently appear to decision-makers as 'black boxes', which transform some input data into some output data. The decision-makers often do not understand how and why a certain output is calculated. As a natural consequence, they can be reluctant to trust it.
- The development and use of all but the simplest models is time- and resource-consuming, and it requires considerable training and expertise. As a consequence, expected benefits from an OR application can often not outweigh expected costs.
- OR is data-hungry. That is, OR often requires numerous input data. These input data are often not easily available (Render et al. 2008). Lack of data has been identified as a major difficulty in OR applications by several surveys (Chen and Wei 2002, Pappis and Dimopoulou 1995). Data can be spread across different legacy systems or not exist as written information at all. Moreover, many data must be estimated, which is often difficult. In many cases, one can justly argue for different estimations. This is

even the case for one of the simplest, most popular quantitative models in logistics, the economic order quantity (EOQ) model (see Subsection 5.3.4). If the EOQ model is to be used to calculate cost-effective production lot sizes, set-up costs and inventory carrying costs are required as input, but often notoriously difficult to estimate (Hopp and Spearman 2001).

- OR requires the problem situation to be clearly defined. OR is less useful for problem identification and prioritization of improvement areas, when the problem situations are only vaguely understood. In terms of Simon's (1977) three phases of decision-making (see Section 4.1), OR addresses mainly the design and choice phase, rather than the intelligence phase (Turban et al. 2007). This is an unfortunate limitation because *'the formulation of a problem is far more often essential than its solution, which may be merely a matter of mathematical or experimental skill'* (Einstein and Infeld 1938).
- OR has few established frameworks, rules or guidelines that support the process of a typical OR application. In other words, little has been written about how OR can be successfully used in practice (Murphy 2005a). For example:
 - a. OR does not help stakeholders reach agreement on objectives and means, which however is a requirement for successful OR application. For example, stakeholders must agree on the nature of the problem situation, and that quantitative modelling can provide added value. Otherwise the results from an OR application may not be used for decision-making.
 - b. OR assumes that input data is available. Relatively little has been written on how to carry out data collection.
 - c. OR provides little formal guidance on formulating appropriate models for a given problem situation. As explained, the choice of the best model is often regarded as an art (Brooks and Tobias 1996), which can only be mastered by gradual acquisition of experience.
 - d. OR does not provide much help on how to introduce model-driven decision support systems successfully in organizations, for example how to make people willing and able to use them.

The survey by Jeffrey and Seaton (1995) asked respondents about the disadvantages to the organization from the use of OR. The following answers appeared most frequently:

- Misuse/erroneous interpretation of results.
- Mismatch between [OR] technique and problem.
- Ignores soft/behavioural issues.
- Used as a substitute for common sense.
- Engenders Analysis Paralysis.
- Time consuming process.

These answers largely confirm the limitations discussed above. Research on the limitations of OR emerged in the 70ties and resulted into attempts to characterize the problem situations that

can benefit from OR, as opposed to those falling outside its scope. This is the topic of the next section.

4.15 General characteristics of problem situations that can benefit from OR

A number of researchers have suggested categorizations of problem situations in order to discuss the applicability of OR. The purpose of these categorizations is to characterize the problem situations that can benefit from OR, and those falling outside its scope. According to Rosenhead and Mingers (2001a), ‘the idea that there is a dividing line is of limited value unless we also have some way of recognizing, based on the characteristics of a particular situation, on which side of the line it falls.’

The simplest categorizations consist of just two categories (dichotomies). Ackoff (1979a) distinguishes between *problems* and *messes*: ‘Managers are not confronted with problems that are independent of each other, but with dynamic situations that consist of complex systems of changing problems that interact with each other. I call such situations messes. Problems are abstractions extracted from messes by analysis; they are to messes as atoms are to tables and chairs. ... Because messes are systems of problems, the sum of the optimal solutions to each component problem taken separately is not an optimal solution to the mess. The behaviour of a mess depends more on how the solutions of its parts interact than on how they act independently of each other.’ He explains that the applicability of OR is limited because OR solves problems, but managers face messes. Unfortunately, however, he does not provide criteria that can be used in practice to assess if OR can be useful in a given context. In a later publication, he explains that the problems suitable for OR tend to be operational and tactical rather than strategic, for example production and inventory control problems; production scheduling; sequencing and queuing problems; allocation of resources; and routing, maintenance and replacement problems (Ackoff 1987). As the following chapters will show, these statements are not fully correct. For example, OR has supported strategic decision-making as well; on the other hand, its usefulness for production scheduling may be lower than expected.

Rittel and Webber (1973) distinguish between wicked and tame problems. A tame problem can be specified, in a form agreed by the relevant parties, ahead of the analysis, and it does not change during the analysis. A wicked problem, in contrast, has many alternative types and levels of explanations, and the type of explanation selected determines the nature of the solution. According to these authors, OR is appropriate only after the wicked problems have been tamed. Again, however, they do not say in which situations it can be worthwhile to ‘tame’ the wicked problem and analyze it with the OR approach.

Similar dichotomies are for example discussed by Schon (1987) - swamp versus high ground - and Ravetz (1971) - practical versus technical problems. Some categorizations with more than two categories have also been proposed. Hopwood (1980) uses two problem situation characteristics related to uncertainty: Uncertainty over the consequences of action, and uncertainty over the objectives of action. These dimensions group problem situations into four types. Table 4-3 shows the decision-making approach he suggests for each of them. It implies that OR is suitable in situations where objectives are clear and consequences of action known.

Table 4-3: Hopwood's (1980) categorization of problem situations

		Consequences of action	
		Known	Unknown
Objectives of action	Known	Compu- tation (OR)	Judge- ment
	Unknown	Bargain- ing	Inspi- ration

Jackson and Keys (1984) developed an influential framework informing about the assumptions made by traditional 'hard' OR and by problem structuring methods: The *System of Systems Methodologies*. Flood and Jackson (1991) later attempt to use this framework to provide some guidance on when to use different systems methodologies. In their version, the System of System Methodologies characterises systems methodologies using two continuous dimensions. These dimensions describe the assumptions made about problem situations:

- From *simple* to *complex* systems: Simple systems follow well defined laws, are unaffected by behavioural influences, are largely closed to the environment, and are not evolutionary. Complex systems, on the other hand, are probabilistic, are subject to behavioural influences, are open to the environment and evolutionary.
- Form *unitary* over *pluralist* to *coercive* participants (stakeholders): Unitary participants share common interests, have compatible values and beliefs and largely agree upon ends and means. Pluralist participants have a basic compatibility of interest, but their values and beliefs diverge to some extent and they do not necessarily agree upon ends and means. Still, compromise is possible. Coercive participants do not share common interests, have conflicting values and beliefs, and genuine compromise is not possible (some coerce others to accept a decision).

The resulting two-by-three matrix can be used to classify systems methodologies. Table 4-4 shows how Flood and Jackson (1991) classify OR and the problem structuring methods they present in their book. OR is placed in the upper left-hand corner, illustrating that OR assumes simple, unitary problem situations. For problem situations that are more complex and more pluralist/coercive, other analysis approaches are claimed to provide a better fit.

Table 4-4: This matrix classifies OR and problem structuring methods according to the assumptions they make about problem situations (Flood and Jackson 1991).

	Unitary	Pluralist	Coercive
Simple	<ul style="list-style-type: none"> ✓ OR ✓ System dynamics 	<ul style="list-style-type: none"> ✓ Strategic assumption surfacing and testing 	<ul style="list-style-type: none"> ✓ Critical systems heuristics
Complex	<ul style="list-style-type: none"> ✓ Viable system diagnosis 	<ul style="list-style-type: none"> ✓ Interactive planning ✓ Soft systems methodology 	

Mingers and Brocklesby (1997) present a similar framework, with particular emphasis on combining several analysis approaches in order to address a problem situation from various angles.

The categorizations reviewed so far are quite pessimistic, in the sense that they limit the scope of OR to a small corner of all problem situations. Murphy (2005a), using a categorization by Mayer (1992), is more positive. Mayer's categorization uses two dimensions: Problem situations can have well-defined or poorly-defined initial states, and well-defined or poorly-defined goal states. An example of each of the four resulting types of problem situations, provided by Murphy (2005a), is included in Table 4-5. According to Murphy (2005a), OR practitioners tend to work with well- or poorly-defined initial states with well- or poorly defined goals, but not both poorly defined. He further argues that soft OR techniques are appropriate when both states are poorly defined, but that such problem situations are not as common as process and technical questions that practitioners can address using standard OR tools.

Table 4-5: Mayer's (1992) categorization, with illustrating examples by Murphy (2005a)

		Initial state	
		Well-defined	Poorly defined
Goal state	Well-defined	Lay out facilities in a factory to minimize material handling	Define project activities and lay out a project management network
	Poorly defined	Schedule production, balancing flow rates and the pattern of late deliveries	Reorganize corporations after a breakup

In summary, the above frameworks suggest that OR can be useful in problem situations with the following characteristics (some of them are related):

- The problem does not change during the OR analysis

- Known consequences of action
- Known objectives of actions
- The system considered
 - follows well-defined laws of behaviour (which is related to ‘known consequences of actions’)
 - is unaffected by behavioural influences
 - is largely closed to the environment
 - is not evolutionary
- Stakeholders
 - Agree on what the problem is
 - share common interests
 - have compatible values and beliefs
- Either the initial state or the goal state are well-defined (well-defined goal state is related to ‘known objectives of actions’)

Clearly such frameworks can increase a general understanding of OR applicability. On the other hand, they do not constitute practical rules managers can use to assess if OR can help them. More specifically, they have the following limitations:

- They are more descriptive than normative. **They describe the assumptions OR makes about the real-world, but they do not say anything about the situations in which it is useful to abstract the real-world system with these assumptions.** As far as the System of Systems Methodologies is concerned, this is even emphasized by one of its creators: Some years after its original publication, Jackson (1990) writes that it is a purely descriptive tool, providing an appreciation of what is being taken for granted in using each approach.
- They use very general characteristics to classify problem situation. As a consequence, they are difficult to use in practice. It is not straightforward to use them as criteria when facing a real-world problem situation. This has also been noted by a contributor himself (Mingers 2003).
- They do not normally distinguish between different OR techniques. Since their developers normally stress the limited applicability of the entire field of OR, this is not surprising. It is, however, not justified from a practical perspective. As a matter of fact, ‘hard’ OR techniques are much more widely known and used than problem structuring methods. Munro and Mingers (2002) found empirical evidence of this fact. This does not qualify OR techniques as better or more suitable in general, but it justifies a more detailed study of the applicability of the different OR techniques. Ormerod (2005) makes similar observations.

The subsequent chapters of this thesis will distinguish between different OR techniques and use much more specific criteria to discuss the manufacturing logistics problem situations in which different OR techniques often can be beneficial.

4.16 Summary

In this chapter, OR has been introduced as an approach to decision support that is based on quantitative models. OR covers a variety of techniques, typically distinguished by the type of model they employ. When OR is used to support decision-making, a number of steps are typically carried out, all within a context consisting of problem situation, application system and intellectual resources. The physical product of an OR application is a model-driven decision support system.

After this general introduction, focus was directed towards this thesis' issue, the applicability of OR techniques. There seems to be a gap between OR literature and OR practice, in the sense that many models in the literature have never been applied. Moreover, OR and its techniques have strengths and weaknesses. The importance of understanding their applicability, in terms of the situations in which they can be beneficial, was therefore emphasized. At a high level, also decision-makers need to have such an understanding because different techniques provide decision support in different ways, are practiced by different people and implemented in different types of software systems. Research on OR applicability and technique selection is scarce, however, and it has not fully succeeded in providing practical guidance on the problem situations in which OR techniques can be useful.

The research carried out in this thesis and presented in the remaining chapters addresses this challenge for manufacturing logistics. Based on a study of close to 200 successful OR applications, it will provide a comprehensive and detailed account of the problem situations that can benefit from the various OR techniques, and how these problem situations are supported by OR. This will hopefully lead to less confusion about the applicability of OR techniques, as well as a reduced gap between literature and practice since there is more certainty about the problem situations where OR works well.

PART III - CONCEPTUAL FRAMEWORK: OR IN MANUFACTURING LOGISTICS

From the key elements of logistics and OR reviewed in part II, one should expect that manufacturing logistics is an important application area of OR, for the following reasons:

- Logistics is management, which OR aims to support
- Logistics focuses on material and information flows. These elements of a manufacturing system would typically be relatively easy to quantify in a model, compared to more human/organizational aspects.
- Logistics takes a systems perspective, from point-of-origin to point-of-consumption, aiming to develop sound solutions for the system as a whole. This thinking in terms of the system as a whole is also at the heart of OR, which develops and analyzes models of system behaviour.
- Logistics addresses numerous trade-offs, such as between costs and customer service. Quantitative models are well-suited to study and understand such trade-offs because they explicitly show how different (conflicting) performance objectives relate to each other.

There has been some empirical research investigating the areas in which OR is applied. Such research strongly confirms this expectation. This thesis' study of successful OR applications published in *Interfaces* revealed 116 OR applications in manufacturing logistics between 1995 and 2007. The study of *Winter Simulation Conference* papers provided additional 51 applications during the years 2002 through 2005. Also some surveys carried out by other researchers provide empirical evidence. Several surveys investigating OR activity in specific countries enquire about application areas and find high usage in areas such as operations management, production and logistics (Stenfors et al. 2007, Chen and Wei 2002, Fildes and Ranyard 1997, Ford et al. 1987). Most of the OR applications carried out by the Dutch OR group studied by Fortuin and Zijlstra (2000, 1989) also fall within manufacturing logistics. Eom and Kim (2006), surveying decision support system applications, found that OR techniques were essential elements of decision support systems, and that most applications fell into the area of production and operations management, followed by marketing, transportation and logistics. Such surveys strongly suggest that OR has been used to support manufacturing logistics extensively for many decades.

On the other hand, the previous chapters identified several challenges, namely the gap between theory and practice, lacking understanding of OR technique applicability, difficulty in selecting techniques, and lacking research specifically investigating the problem situations in which OR techniques work well.

Part III makes first steps in addressing these challenges by developing rigorous, purposeful concepts and classifications (the first specific objective defined in the introduction). Chapter 5 proposes a classification and characterization of the typical OR techniques used to support manufacturing logistics. Chapter 6 proposes a classification of manufacturing logistics decisions supported by OR. These two classifications constitute a framework that will allow addressing the above challenges rigorously, which will be done in parts IV and V.

5 OR techniques used to support manufacturing logistics

This chapter proposes a classification and characterization of the OR techniques used most often in practice to support manufacturing logistics.

First, the purpose of such a classification is explained and detailed criteria deduced from it that the classification should satisfy. Next, relevant previous literature is reviewed and assessed. The third section describes how the classification was developed, as well as the classification itself, with detailed descriptions of each class. After a characterization and comparison of these classes in Section 5.4, the quality of the proposed classification is checked by means of the criteria developed in the first section. The chapter concludes that the developed classification contributes to the overall objective of this thesis, but pinpoints at the same time a number of insufficiently addressed issues that need further attention.

The main contribution of this chapter is thus in Sections 5.3 and 5.4, which present the classification and characterization of OR techniques, including precise definitions of content and scope of each technique, discussions of strengths and limitations, and a comparison of the different techniques' philosophical assumptions and characteristics.

5.1 Purpose

The purpose of the classification of OR techniques to be developed is twofold. First, it should highlight the techniques most frequently used to support manufacturing logistics, providing a first appreciation of OR technique applicability. Second, it should contribute to a rigorous and purposeful framework for more detailed investigations and discussions on technique applicability.

Based on these goals, a number of detailed criteria can be established:

- (1) The classification should highlight the OR techniques that are used in practice to support manufacturing logistics. This criterion follows directly from the first purpose.
- (2) The different classes should be mutually exclusive and so clearly defined that most models can be classified easily. This is a general requirement to classifications (Cooper and Schindler 2003).
- (3) The classification should be at a high level, of interest from the perspective of operations management. As explained in Section 4.12, this means that different techniques should have different world views, be practised by different people and implemented in different types of software systems. This criterion reflects the operations management perspective taken in this thesis. More detailed classifications would be predominantly interesting from an OR perspective.
- (4) It should – as far as possible – use common and established terms/definitions. This simplifies communication and acceptance of the classification.

The next section will review classifications of OR techniques used in the literature.

5.2 Literature review

OR technique classifications are used in several contexts in the literature, such as in textbooks, papers reviewing models and papers describing surveys of OR practice. The

grouping of techniques presented in Section 4.6, repeated in Table 5-1, is based on textbooks. Table 5-1 also shows a number of groupings used in surveys of OR practice.

Table 5-1: Examples of OR technique classifications

<p>The classification in this thesis' theory part Optimization (mathematical programming)</p> <ul style="list-style-type: none"> • Linear programming • Mixed-integer programming • Integer programming • Non-linear programming • Combinatorial optimization • Multiobjective programming (goal programming) • Stochastic programming <p>Network models Simulation</p>	<ul style="list-style-type: none"> • 'Spreadsheet' simulation • Monte Carlo simulation • Discrete-event simulation • Continuous simulation <p>Inventory theory Queuing theory Game theory Dynamic programming Markov Chains Forecasting Decision analysis</p>
<p>Olhager and Rapp (1995) Mathematical programming Simulation Statistics Network analysis Queuing Stochastic processes Inventory control</p>	<p>Probability Regression analysis Forecasting models Heuristics Artificial intelligence Expert systems Visual interactive modelling</p>
<p>Eom and Lee (1990) Deterministic models</p> <ul style="list-style-type: none"> • Linear programming • Goal programming • Transportation model • Network model • Inventory models • Integer programming • Nonlinear programming • Dynamic programming <p>Stochastic models</p> <ul style="list-style-type: none"> • Queuing models <p>Markov process models</p>	<ul style="list-style-type: none"> • Simulation models • Decision trees • Game theory <p>Forecasting and statistical models Others</p> <ul style="list-style-type: none"> • Other multi-criteria decision making models • Spreadsheet modelling • Graphics • Artificial intelligence
<p>Fortuin and Zijlstra (2000 and 1989) Mathematical programming Combinatorics Inventory control models</p>	<p>Probability models Discrete simulation Miscellaneous</p>
<p>Munro and Mingers (2002) Inventory Discrete event simulation Heuristics / combinatorial optimization Statistical analysis Mathematical programming Project network</p>	<p>Forecasting Queuing theory System dynamics Decision analysis ... and numerous techniques from 'soft' OR</p>

These and similar groupings work well for certain purposes, for example for providing a general overview of OR techniques or for structuring textbooks. On the other hand, it is not straightforward to classify models according to them because they do not satisfy criterion (2), i.e. the terminology is often not precisely enough defined by the authors who use it, and the classes are not mutually exclusive. Munro and Mingers (2002), for example, use ‘combinatorial optimization’ and ‘mathematical programming’ as two distinct OR techniques; where, then, should an integer program be classified? Olhager and Rapp (1995) distinguish between ‘mathematical programming’ and ‘heuristics’; in which of these classes does a mathematical program fall that is solved with a heuristic? Note that also the grouping of techniques proposed in Section 4.6 has its flaws. For example, where should an inventory model solved by dynamic programming be classified?

A related problem is that there is some disagreement on the meaning of terms in the literature. For example, there are many different definitions of the term simulation. Some authors call any descriptive model a simulation model. Bookbinder et al. (1989), for example, use the term simulation for a static deterministic descriptive model. Others only include dynamic models in their definitions (Robinson 2004). Olhager and Rapp (1995) therefore correctly observe that the term ‘simulation’ is given a variety of meanings: From simple, deterministic what-if calculations to stochastic discrete-event simulation.

These issues decrease the validity and meaningfulness of survey results, and they make comparison between different surveys difficult. Clark and Scott (1999), Fildes and Ranyard (1997), and House (1978) all comment and criticize this lack of a standard and established classification of OR techniques. It constitutes a serious impediment to more rigorous investigation of the applicability of OR techniques.

Due to this lack of standardization, studies reviewing literature on models usually develop and define their own classifications. Ojala (1992), for example, studies modelling approaches in port planning and analysis. He distinguished mainly between econometric, analytic and simulation models. This classification largely satisfies criteria (2) through (4), and constitutes thus for port planning and analysis what the classification to be developed should be for manufacturing logistics. More generally, there are numerous parallels between Ojala’s work and the present study since both focus on OR technique applicability and take a high-level perspective.

Min and Zhou (2002) classify and review literature on supply chain models and address thus a scope relevant for manufacturing logistics. The main purpose of their classification (Figure 5-1) is, however, to structure the reviewed papers, not to provide a rigorous taxonomy that allows classifying models and discussing their applicability. For the latter purpose, it does not comprehensively and precisely enough define the different classes.

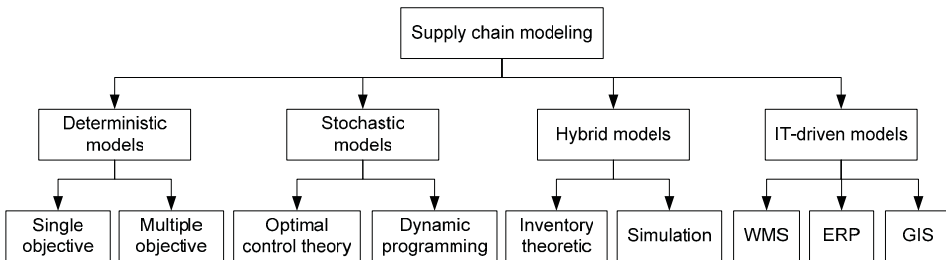


Figure 5-1: Min and Zhou’s (2002) classification of supply chain models

Turban et al. (2007) also present a categorization of OR techniques (Table 5-2). The classification criterion they use is the solution procedure, that is, models are distinguished according to the procedures used to solve them. While the categories are easy-to-use and largely mutually exclusive (criterion 2), the researcher does not consider the distinction between different solution procedures as the key issue from an operations management perspective (criterion 3). For example, distinguishing between heuristic and exact procedures may often be of limited relevance to the decision-makers, since even exact solutions are based on simplifying assumptions about the real world, possibly even greater simplifications than if a heuristic procedure had been used. In Simchi-Levi et al.'s (2008) terms, 'exact solutions to approximate problems may be worth no more than approximate solutions to approximate problems.'

Table 5-2: Classification of OR techniques according to different solution procedures (Turban et al. 2007)

Category	Process and objective	Representative techniques
Optimization of problem with few alternatives	Find the best solution from a small number of alternatives	Decision tables, decision trees
Optimization via an algorithm	Find the best solution from a large number of alternatives using a step-by-step improvement process	Linear and other mathematical programming models, network models
Optimization via an analytic formula	Find the best solution in one step, using a formula	Some inventory models
Simulation	Finding a good enough solution or the best among the alternatives checked, using experimentation	Several types of simulation
Heuristics	Find a good enough solution, using rules	Heuristic programming, expert systems
Predictive models	Predict the future for a given scenario	Forecasting models, Markov analysis
Other models	Solve a what-if case, using a formula	Financial modelling, waiting lines

In conclusion, there is a gap between the classifications in literature and the needs of the present research. The next section proposes a classification which satisfies all the four criteria.

5.3 *The classification*

This section formulates a classification of OR techniques that satisfies the criteria specified at the beginning of this chapter. It includes precise definitions and motivations of content and scope of each technique, discussions of strengths and limitations as well as some general comments on the situations in which each technique is suitable.

The actual process of developing the classification started from existing classifications such as the ones reviewed above. The OR applications included in the survey of *Interfaces* (see Chapter 7) were then used to identify the OR techniques most frequently employed to support manufacturing logistics (criterion 1). This was done in a highly iterative process between

studying OR applications and working out detailed definitions of relevant techniques, so as they would satisfy the above four criteria. In particular, the scope of relevant techniques had to be specified clearly in order to avoid overlap (criterion 2) while at the same time combine techniques with similar ‘paradigmatic’ properties (criterion 3). So the process was inductive and resembled in some aspects that of grounded analysis/theory (Easterby-Smith et al. 2002, Strauss and Corbin 1998). It resulted in the following classification:

- Deterministic optimization
- Discrete-event simulation
- Inventory theory
- Queuing theory

Section 5.5 will argue that this classification satisfies the specified criteria. In particular, the four techniques it distinguishes stand for the majority of OR applications in manufacturing logistics. A number of other techniques are occasionally used, such as continuous simulation (system dynamics). They are collected in a ‘miscellaneous’ class, consisting of all techniques that do not fall into any of the other classes.

The four main classes are now presented in detail, with focus on their scope. The presentation of each technique briefly touches upon typical

- model characteristics
- solution procedures
- software systems

Strengths and limitations stated in the literature are also reviewed. They are mainly related to validity, tractability, skills and resources required for model development and use, data requirements and visualization opportunities. When reviewing the literature on the different techniques’ advantages, the researcher sometimes had an impression of advertising rather than objective treatment. In the review below, only advantages that help understanding the appropriateness of a technique are included. Moreover, general advantages of quantitative models are not repeated (they were presented in Section 4.13); focus is on advantages and limitations that are specific for a particular technique in comparison to other techniques.

Some comments on the problem situations in which each technique is useful are also made, mainly based on literature. The criteria discussed here concern the techniques in general, not within a specific application area. For manufacturing logistics, much more detailed criteria will be discussed throughout the remainder of this thesis.

For further details on the mathematical aspects of these techniques, consult OR textbooks (Render et al. 2008, Winston 2004). There is no need to be acquainted with the techniques’ mathematics in order to understand this thesis. In fact, one of its aims is precisely to explain in plain English how they work.

The remainder of this section is based on numerous relevant textbooks (Render et al. 2008, Turban et al. 2007, Banks et al. 2005, Robinson 2004, Winston 2004, Brooks et al. 2001,

Shapiro 2001, Law and Kelton 2000, Rardin 1998, Gershwin 1994, Buzacott and Shanthikumar 1993).

5.3.1 Deterministic optimization

From the definition of optimization provided in Section 4.6 it can be seen that optimization models consist of three elements:

- *Objective function*: A mathematical expression in the decision variables and input parameters. For example, the sum of different cost types. The goal of optimization is normally to maximise or minimize this expression.
- *Constraints*: Mathematical equations or inequalities expressing system properties which have to be respected, for example capacity limits.
- *Decision variables*: The variables for which values are sought that maximize/minimize the objective function while respecting the constraints.

These three elements constitute a structured way of presenting optimization models. As Section 4.6 also showed, optimization includes numerous classes of models. Usually, properties related to the above elements are used to distinguish between classes, for example linear/non-linear mathematical expressions, continuous/integer decision variables, constrained/unconstrained optimization, one/several objective functions, deterministic/stochastic parameters etc.

In practice, mainly deterministic models are used. Within the context of manufacturing logistics, some empirical evidence of this fact is given in Section 5.5. Rardin (1998) observes it more generally. This is why this class is restricted to deterministic optimization models.

Example of a deterministic optimization model (Chopra and Meindl 2010)

A classical example of an optimization model is the *capacitated facility location model*. Given are a number of existing or potential future facility locations and a number of customer regions. The model helps decide which customer regions to serve from which facilities, and if existing facilities should be shut down or new facilities opened.

Before decision variables, objective function and constraints can be defined, indexes and data need to be specified.

Indexes

- n = number of existing and potential future facility locations
- m = number of customer regions

Data

- D_j = annual demand from region j
- K_i = Maximum capacity of facility i
- f_i = annualized fixed cost of keeping facility i open
- c_{ij} = cost of producing and shipping one unit from facility i to region j

Decision variables

- y_i = 1 if facility i is open, 0 otherwise
- x_{ij} = quantity shipped from facility i to region j

Objective function

$$\text{Min} \sum_{i=1}^n f_i y_i + \sum_{i=1}^n \sum_{j=1}^m c_{ij} x_{ij}$$

Constraints

$$\sum_{i=1}^n x_{ij} = D_j \quad \text{For all } j = 1, \dots, m$$

$$\sum_{j=1}^m x_{ij} \leq K_i y_i \quad \text{For all } i = 1, \dots, n$$

$$x_{ij} \geq 0 \quad \text{For all } i = 1, \dots, n \text{ and } j = 1, \dots, m$$

$$y_i \in \{0, 1\} \quad \text{For all } i = 1, \dots, n$$

In this example, the objective function is the sum of fixed facility costs and variable operating costs. This function is to be minimized. The first constraint states that demand has to be met in all regions. The second makes sure that the maximum capacity of each facility is not exceeded (if a facility is not open, the expression on the right of the inequality symbol is equal to 0). The remaining two constraints limit the values the decision variables can take. In particular, the decision variables y_i can only take the values 0 or 1.

This example is a mixed-integer linear program.

An important characteristic of optimization models is that they are normative, i.e. some procedure can automatically determine ‘good’ or ‘optimal’ values for the decision variables. Many different such solution procedures have been developed for various types of optimization models, some of them exact, others heuristic. A famous exact solution procedure is the *Simplex* algorithm, which solves linear programs.

Note that some normative models cannot be easily expressed by means of the three elements above, for example some models solved using dynamic programming. Such models are still classified as deterministic optimization because they are normative and seek to find optimal values of some decision variables.

Thus, deterministic optimization is a big class including all deterministic normative models, unless they clearly belong to inventory theory. Normative inventory models are more naturally classified as inventory theory, which is also most appropriate in order to satisfy criteria (3) presented at the beginning of this chapter. Note also that a finer grouping of optimization models would be interesting, but mainly from an OR perspective. Technique selection at a finer level would typically be done by modellers and may be considered as part of the next step of a modelling analysis, conceptual model design (see Section 4.8). Due to the high-level focus of this thesis, for which the researcher argued in Section 4.12, such a finer grouping was not done. For example, as explained before, the researcher’s opinion is that distinguishing between heuristic and exact solution procedures is often not crucial for the decision-makers, since even exact solutions are based on simplifying assumptions about the real world, possibly even greater simplifications than if a heuristic procedure had been used. Compared to the ‘errors’ due to model assumptions and imprecise input data, the difference

between a heuristic and an exact solution may be insignificant (Rardin 1998). Or, as stated before, ‘exact solutions to approximate problems may be worth no more than approximate solutions to approximate problems’ (Simchi-Levi et al. 2008). Nevertheless, at least from an OR perspective, finer classifications provide interesting paths for further research.

Optimization models are implemented in different types of software systems. For simple instances, spreadsheets can sometimes be used. MicroSoft Excel, for example, allows solving small linear programs with the *Solver* function. In many cases, however, there is a need for more specific software systems. *General-purpose optimization packages* can be used to solve a variety of optimization models. They typically contain a modelling language for model implementation (for example AMPL or Mosel), a solver for model solving (such as Cplex, Xpress or Lindo) and various tools for model analysis. There are also optimization-based commercial systems that are dedicated to a particular application area. They contain models, solution procedures and user interfaces tailor-made to this application area. Examples include facility location systems as well as most modules in APS systems (see Section 4.7). Customized solution procedures, for example specially developed heuristics, often need to be implemented by means of programming languages.

Strengths

The major advantage of optimization models is that they include some procedure automatically searching for goods or even optimal solutions (‘optimal’ within the given assumptions and input data). This makes quick identification of desirable solutions possible even when there are a lot of decision variables and options. The decision-makers do not need to specify solutions themselves, and many alternatives can be considered within short time. Often, exact algorithms can be used, guaranteeing that all alternatives are considered and the very best selected (again, within given assumptions and input data). In other situations, heuristics may have to be use, but they can still quickly identify good solutions. Heuristics may be just as useful as exact procedures to decision-makers, since even exact models are simplifications from the real world (see above).

In many situations, linear and mixed-integer programs appear to be good enough representations of reality, even though the relationships in the real-world system may not be perfectly linear. Such deterministic optimization models can normally be solved easily, and there are good opportunities for sensitivity analysis. They have good tractability, much better than for example discrete-event simulation.

Another advantage compared to discrete-event simulation and queuing theory is that different costs can be modelled and traded-off, such that lowest-cost alternatives can be selected. Optimization provides a means to focus on cost reduction/minimization, which is often desirable in practice. In discrete-event simulation and queuing theory, costs are usually more difficult to incorporate in the models.

The fact that optimization seeks goods solutions automatically, implies that decision-makers can obtain answers from the models without knowing all the mathematical subtleties or having to do much manipulation in the model. User-friendly interfaces can be developed, allowing decision-makers obtaining answers from the models themselves, which is especially useful for operational decision-making. More manipulation will normally be necessary if discrete-event simulation is used, and answers may not be obtained as readily.

Last, but not least, optimization models can incorporate a lot of decision variables and parameters and find good or even ‘optimal’ solutions taking into account the interrelationship between them all. According to Shapiro (2001), ‘they are the only analytical tools capable of fully evaluating large, numerical databases to identify optimal, or demonstrably good, plans.’

Limitations

A significant limitation of optimization models is that considerable simplifying assumptions normally have to be made in order to make them solvable. That is, in order to allow some procedure calculate desirable solutions, the models need to have certain ‘nice’ properties. An example of such a property is that mathematical expressions are linear. As explained earlier, models with this property are usually easy to solve by means of the Simplex algorithm. The problem is that the world is not linear, and there is the danger that the model and its answers are too far from reality. So, especially compared to discrete-event simulation, optimization has generally lower validity.

In particular, many optimization models are static, i.e. they look at a fixed point in time (or one time period) and use averages for input data (for example average annual demand). Some optimization models are time-phased, but they in return often require other unrealistic assumptions in order to be solvable.

In deterministic optimization models, so all input data has to be specified by means of a fixed value. The model solutions are therefore only sure to be good or ‘optimal’ for these input values. Solutions for alternative input values can of course be calculated. Still, such models cannot calculate solutions that are good or ‘optimal’ given the random behaviour of certain or all input variables. This makes them for example little appropriate to calculate how much excess capacity or inventory (safety stock) is needed to cope with random variations in demand and supply.

Other limitations include:

- The development of optimization models can be quite time-consuming and normally requires considerable technical knowledge and experience. This also drives costs.
- While many optimization models can be solved relatively quickly, it normally takes more time than solving the typical formulae used in queuing theory and inventory theory. Optimization models used in practice can include hundreds or thousands of variables and constraints, which can make them rather slow.
- The advanced mathematical concepts normally used in optimization can be difficult to grasp for decision-makers. As a consequence, the solutions seem to appear from a ‘black box’, which can reduce the decision-makers’ confidence in it. While discrete-event simulation allows intuitive animated displays, optimization models are usually communicated by means of mathematical expressions. They are an intangible product, which is typically more difficult to communicate than more tangible solutions (Murphy 2005c).
- Data hungry: As opposed to inventory theory and queuing theory, optimization models often involve a lot of input data. This can be considered as strength, but also a limitation due to the notorious difficulty of obtaining and handling large amounts of data.

- Optimization models have somewhat limited flexibility, especially compared to discrete-event simulation. That is, changes in the real-world may be difficult to incorporate in the model, and the model may not that easily be adapted to address a related, but different problem situation.

In which problem situations?

It is often stated that optimization should be used whenever an optimization model can be developed that accurately enough represents the real-world system. Stadtler (2005a), for example, explains that linear programming is applicable in decision situations where decision variables can take any real values only restricted by linear (in-)equalities, e.g. for representing capacity constraints. However, when is it appropriate to make such an assumption? While certainly true, such general statements provide by themselves relatively little help in deciding whether to use optimization for decision support.

A useful criterion is the number of decisions. Having many decisions usually leads to optimization (Murphy 2005b). In more precise terms, optimization is useful when there are a lot of inter-related decisions (decision variables) that need to be coordinated. Optimization considers all these decisions collectively and suggests solutions that are good or ‘optimal’ for the system as a whole.

A second criterion is that deterministic optimization works well when dealing with large quantities, where averages are appropriate. Murphy’s (2005b) example is the use of linear programming for manpower planning in the military, because it deals with large numbers of people.

Often, optimization models are used to allocate scarce resources (the constraints) among competing activities (the decision variables) to optimize a measurable goal (the objective function).

Finally, the properties of deterministic optimization suggest that it works best when system dynamics and random behaviour are not a key issue.

5.3.2 Discrete-event simulation

Discrete-event simulation is one of two basic types of dynamic simulation (continuous simulation is the other one). *Dynamic simulation* can be defined as ‘experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for the purpose of better understanding and for improving that system’ (Robinson 2004).

Discrete-event simulation models usually represent a real-world system as a queuing system. A queuing system consists of a set of *resources* (machines, people, equipment) where *entities* (materials, information, people) are processed, move between the resources, and form *queues* in front of them (Figure 5-2). Note that a large variety of real-world systems can be considered as queuing systems, such as shops, restaurants, manufacturing systems, hospitals, telephone switchboards, etc.

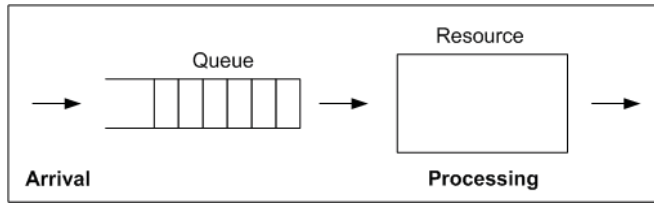


Figure 5-2: A simple queuing system

Resources, entities and queues are the basic concepts used in discrete-event simulation. At any point in time, a discrete-event simulation model is in a certain *state*. The state of the model is given by the collection of variables necessary to describe the status of the system at any given time (Winston 2004). It is changed by *events* occurring at *discrete* points in time, for example the arrival of an order, the start or end of an activity etc. This is why these models are called *discrete-event* simulation models. The relationships between variables in the model is represented by means of mathematical and logical (if...then...else) expression.

Pure discrete-event simulation models are descriptive, i.e. they allow the analyst to evaluate the performance of fixed decision alternatives. Various experiments are typically carried out with different values for the decision variables, eventually providing an adequate picture of how the system behaves and which values lead to good performance. In basic models, there is no automatic procedure searching for good values (solutions). In order to facilitate the search for particularly desirable solutions, discrete-event simulation models are sometimes enhanced with normative solution procedures. For example, Mollaghasemi and LeCroy (1998) used neural networks with their discrete-event simulation model. *Simulation optimization* is defined as a structured approach to determining optimal input parameter values, where ‘optimal’ is measured by a function of output variables associated with a [discrete-event] simulation model (Swisher et al. 2000). Discrete-event simulation models that are enhanced with some normative solution procedure are classified as discrete-event simulation because the way the real-world system is represented (the ‘view’) is the same as in purely descriptive discrete-event simulation models.

Various types of software systems have been used to implement discrete-event simulation models. Very simple models can be implemented in spreadsheets. More advanced models are often implemented in *general-purpose discrete-event simulation software systems*. In such systems, models are built and run in a visual, interactive manner, with predefined objects and menus. The need for programming skills is rather low, and model building is made quicker and easier. Different vendors offer systems with different degrees of specialization. *Quest*, for example, is a tool especially developed for manufacturing systems. *Arena* is more general, but has also manufacturing-specific modules. For some very advanced or unusual applications, discrete-event simulation models sometimes need to be programmed in computer languages such as C.

Strengths

Discrete-event simulation models can include many aspects of system behaviour, which allows them to be highly realistic (high validity). There are mainly three reasons for this:

- Most real-world systems experience considerable variability, for example in demand. Discrete-event simulation represents variability explicitly by means of stochastic

variables or time series. This is vital when attempting to predict performance because using averages can lead to wrong results.

- Most real-world systems are dynamic, i.e. they evolve over time. Since discrete-event simulation is a dynamic modelling technique, it can represent interactions of components over time.
- More generally, few assumptions and simplifications are required. Most aspects of a real-world system can be modelled if this is deemed useful, such as detailed control policies in operations. As opposed to queuing theory and inventory theory, there is usually no need to assume particular probability distributions for stochastic variables. It is also possible to use actual historical data, for example historical demand series. Note, however, that it has been argued that most simulation models do not correctly model control policies (Gershwin 1994).

In general, discrete-event simulation can include more aspects of system behaviour and requires fewer simplifications than any of the other techniques in the classification.

Additional advantages include:

- The flexibility of discrete-event simulation models makes them easy to be extended or adjusted to changes in the real system.
- The amount of theoretical knowledge in the area of discrete-event simulation is more manageable than for the other techniques.
- Simulation allows an animated visualization of the system, giving a non-expert greater understanding of, and confidence in, the model. At least partly, this has contributed to the success of discrete-event simulation in practice.

Limitations

The validity of discrete-event simulation comes at the expense of tractability. Discrete-event simulation is basically a descriptive technique, so there is usually no procedure that automatically searches for good solutions. Model analysis is restricted to what-if analysis, and there is no guarantee that one finds the 'optimal' solution, not even within the model world.

There is also the danger that simulation models get so complex that it is hard to know what is in them. As a consequence, they may be modified and debugged until they correspond to the modellers' or users' expectations. Such a model would reproduce their prejudices more than inform about reality (Gershwin 1994).

Other limitations include:

- The cost: Simulation software, model development and use (especially if done by external analysts), can be expensive.
- The time: Model development and use can be rather time-consuming. This adds to costs and means that benefits are not immediate. Especially model *use* is often faster and cheaper if any of the other three techniques is used, and it requires less expertise/training. Discrete-event simulation usually requires each scenario of interest

to be simulated several times (replicated runs) in order to achieve a desired statistical significance, which can take some time.

- Data hungry: Discrete-event simulation often requires significant amounts of data, at least compared to inventory theory and queuing theory.
- Skills required for model development: Skills are required in conceptual modelling, validation, statistics and model implementation in software.
- Skills required for model use: Often, simulation models have to be used by their developers and other analysts, rather than the decision-makers. This drives costs and makes their use in decision-making more cumbersome. Special interfaces sometimes allow decision-makers to make small changes themselves, for example in parameter values, but changes in model structure usually need to be made by the original model developer.

In which problem situations?

(Discrete-event) simulation is often stated to be method of last resort, rather than the preferred option (Pidd 1998). By this is meant that it should only be used when the problem situation cannot be validly modelled with other techniques, for example because there are too many interactions among variables, and variability, randomness and uncertainty are important. ‘If the system being modelled is subject for significant levels of variability, then simulation is often the only means for accurately predicting performance’ (Robinson 2004). These criteria provide some guidance on when to use the technique. However, many real-world systems exhibit the above properties. This leads some to conclude that simulation is often the *only* resort (Robinson 2004, Law and Kelton 2000). The author of this thesis takes a somewhat more critical perspective, and rather concludes that to decide whether to use it or not, looking at the above properties is often not enough.

According to Murphy (2005b), discrete-event simulation should be considered if there are many time stages and few choices. The latter criterion, few choices, is useful. Since discrete-event simulation is a descriptive technique, finding good solutions can be a daunting task with discrete-event simulation if there are many alternatives. If there are few choices, on the other hand, each of them can be simulated and assessed separately, and a good understanding of the ‘pros’ and ‘cons’ of each alternative can be obtained.

Discrete-event simulation can be usefully combined with other techniques. In this case, it would often (but not always) be used to verify and fine-tune solutions identified by, for example, optimization.

5.3.3 Queuing theory

As discrete-event simulation, queuing theory also views the real system as a queuing system. That is, queuing models also abstract a real-world system as a set of *resources* (machines, people, equipment) where *entities* (materials, information, people) are processed, move between the resources and form *queues* in front of them (Figure 5-2). Instead of imitating a system as it progresses over time, however, queuing theory describes the relationships in the system using mathematical functions (formulae). Three concepts are central in queuing systems/theory:

- Arrival process: A new entity entering the queuing system

- Service process: The resources processing the entities
- Queue discipline: The rule determining in which order to process entities queuing before a resource, such as first-come-first-served.

Typical input data for queuing models are processing times at resources, inter-arrival times of items to be processes at these resources and queue disciplines. Variability in the system, especially inter-arrival times of entities and processing times at resources, are expressed using stochastic variables. Queuing theory uses the *steady-state property* of most queuing systems: Once a queuing system has been ‘up and going’ for a while, its behaviour is independent from the state it was in initially. Queuing theory calculates steady-state probabilities of queue lengths, waiting times, cycle times and throughput times, capacity utilizations and other performance measures of relevance in queuing systems. What-if analysis can be used to calculate these performance measures for different system configurations, for example by varying the number and capacity of resources.

Example of a queuing model

The simplest results from queuing theory concern a single resource with exponentially distributed inter-arrival times, with a mean of L entities per period, and exponentially distributed processing times, with a mean of M entities per period. In this case, the following results apply (Winston 2004):

$$\text{Average queue length: } \frac{L}{M-L}$$

$$\text{Average waiting time: } \frac{L}{M(M-L)}$$

If, for example, the average inter-arrival time is 12 minutes and the average processing time 10 minutes, the average queuing length is 5 and the average waiting time $5/6$ periods. This is typically more than one would expect. It illustrates how queuing theory can quickly and easily provide a feeling of system behaviour. If variability had been ignored in the above example, one may have erroneously concluded that there will be no queue or waiting time at all. Note, however, that the results are based on the assumption of exponentially distributed arrival and service processes.

Used this way, queuing models are descriptive. In addition, solution procedures are sometimes developed for normative purposes; often, such procedures calculate capacity requirements. For example, a normative procedure may determine how many machines are required to achieve a certain throughput time.

The scope of queuing theory as defined in this thesis also includes Markov process models of production lines, such as those presented by Gershwin (1994) and by Dallery and Gershwin (1992), because such models match the above characterisation of queuing models well. They have also been published under this heading before (Dallery and Gershwin 1992).

Queuing models have been implemented in specific software systems with user-friendly interfaces. Suri et al. (1995) discuss some of their development up to 1995. Today, software with the basic queuing models can be downloaded from the web for free. For more specific applications, spreadsheets, programming languages or mathematical software such as *Mathematica* may be used.

Strengths

The main advantages of queuing theory are speed and ease of use as well as limited data requirement:

- (1) Speed of use: Since queuing theory uses mainly mathematical functions and formulae (rather than algorithms or simulations), it can provide answers within seconds.
- (2) Ease of use: Once a model is implemented, input variables can easily be changed by the decision-makers, allowing them to carry out numerous what-if analyses themselves. Software based on queuing theory is simple and requires little training.
- (3) Little data required: Most queuing models require just a few input parameters, for example inter-arrival time, processing time and queuing discipline.

Since queuing theory represents the queuing system by means of mathematical functions, the relationships between different variables are easy to see. In discrete-event simulation, many experiments may have to be carried out before such an understanding is obtained. Thus, queuing theory has often better tractability than discrete-event simulation.

Limitations

The main limitation of queuing theory is that it can only accurately represent systems with particular properties, mainly simple systems (see ‘In which problem situations?’ below). Its results often assume random variables to follow certain specific probability distributions, such as the exponential distribution. Many queuing systems therefore simply cannot be modelled validly by queuing theory.

Other limitations include:

- The development of all but the simplest queuing models requires quite some mathematical knowledge and modelling experience. While for other modellers, a queuing model may be easier to understand than a discrete-event simulation model, the opposite is usually the case for decision-makers.
- With queuing theory, it is often more difficult to predict the time required to come up with a useful model than if discrete-event simulation was used (Buzacott and Shanthikumar 1993).
- Queuing models are not flexible: Small changes in the structure of the system modelled may require a totally new model.
- Queuing models are often descriptive. This limitation can be mitigated relatively easily, however, since their speed allows automatic or user-guided exploration of many alternatives within a short time (Alden et al. 2006).

In which problem situations?

Queuing theory was initially used to analyze performance of computer systems and communication networks. In manufacturing, it was first used in the context of flexible manufacturing systems, then to analyze KANBAN systems. During the 90ties, its applicability boosted as manufacturing companies started to focus more on time reduction, rather than cost reduction only (Suri et al. 1995).

Queuing theory is useful only in a limited number of situations, but in these situations it is used quite intensively (Littlechild and Shutler 1991). It is appropriate when it can accurately enough represent the real-world system. Typically, the system has to be simple, which means for example:

- Few resources
- Simple queuing disciplines
- Only one type of entities
- Constant capacities at resources (for example no extra capacity in rush periods)

In more complex situations, discrete-event simulation is used. It can be considered as the main alternative to queuing theory, but the two techniques have also been used in combination. Typically, queuing theory can be used to quickly obtain some approximate answers, which can then be validated and fine-tuned by means of discrete-event simulation.

5.3.4 Inventory theory

The purpose of inventory theory is to help decide how much stock to keep so that affected costs are minimized and customer demand met. Typical issues addressed include how much to order/produce, when to order/produce and how much safety stock to keep.

Inventory models can be grouped into deterministic and stochastic models (Winston 2004). Deterministic models are often extensions of the famous *economic order quantity* (EOQ) model, which calculates how much to order/produce so that the best trade-off between inventory costs and reorder/set-up costs is achieved:

$$EOQ = \sqrt{\frac{2 \cdot D \cdot K}{h}}$$

where D is the demand per period, K the reorder cost per order, and h the unit inventory carrying cost per period. For details, see Simchi-Levi (2008) or Hopp and Spearman (2001).

Stochastic inventory models often calculate appropriate stock levels so that an optimal trade-off between inventory costs and product availability is achieved. For example, the following formula is frequently used to calculate safety stock (SS) requirements:

$$SS = z \cdot STD \cdot \sqrt{L}$$

In this formula, demand per period is assumed to be normally distributed with a standard deviation equal to STD. L is the replenishment lead time. z is the safety factor, which is chosen from statistical tables to ensure that the probability of stock-outs during lead time is equal to a given level. See again Simchi-Levi (2008) for further details. Stochastic inventory models can represent the effect on stock outages of variances in demand and lead times; this is not done easily with deterministic optimization models.

Single-stage inventory models, such as the two above, address each inventory location separately; see, for example, Winston (2004) for an introduction. More recently, *multi-echelon inventory models* have appeared. They model inventories across supply chains rather than at a single location. Typically, they are used to determine safety stock inventory

locations and levels such that a desired service level (in terms of product availability to external customers) is achieved at lowest inventory costs for the supply chain as a whole. They take a holistic supply chain perspective and avoid sub-optimization, which can easily occur when each location calculates safety stock requirements independently. They can also be used to assess the effect on required inventory investments from various changes in the supply chain. Graves and Willems (2003) review multi-echelon inventory models.

Most inventory models are normative. For some models, closed-form solutions exist that directly calculate the ‘optimal’ solution (for example the EOQ formula). In other cases, algorithms are used. Especially in multi-echelon inventory theory, these algorithms can be rather complex, but they usually remain fast.

Simple inventory models can be implemented in spreadsheets. They are also included in many purchasing and inventory management systems used in practice. More advanced models and solution algorithms may need to be implemented by means of programming languages. Recently, a number of commercial software systems based on multi-echelon inventory theory have appeared. They often have user-friendly interfaces that allow inventory analysis across the supply chain without the need to understand the algorithms used to calculate good solutions.

Strengths

Inventory theory offers simple formulae for calculating when and how much to order. These formulae are fast, easy to understand, easy to use and require little input data. They are robust in the sense that despite uncertain input data and simplifying assumptions, their answers provide good approximations. Most Inventory models are normative and can be implemented in decision support systems that quickly and automatically calculate when to replenish the warehouse and by how much, typically for thousands of stock-keeping units. Using inventory models is thus cheap and does not require advanced mathematical knowledge. These properties make them very popular in practice.

Inventory models represent inventory issues better than the typical techniques in deterministic optimization, such as linear programming. They can model variability in demand and lead times by means of stochastic variables, and they use non-linear functions (Inventory-related issues often do not behave in a linear way. For example, order costs per period are not a linear function of order quantity).

Inventory models explicitly represent inventory and the costs associated with it. This can help managers see and understand the cost and value of inventory in the manufacturing system, which otherwise can easily be underestimated.

Limitations

The simple formulae so popular and common in practice make a lot of unrealistic assumptions. EOQ, for example, assumes constant, deterministic demand and instantaneous replenishment, among many other assumptions (Hopp and Spearman 2001). In addition, inventory costs and reorder/set-up costs are assumed to be known, but they can be difficult to estimate in practice. More advanced models relax some of the assumptions, but they quickly get complex and are not as practical any more. Also stochastic and multi-echelon inventory models make assumptions that can be unrealistic; for example, most of them assume normally distributed demand.

Since inventory models are easy to use, there is the danger that too much reliance is put on their results. For example, EOQs are frequently used to determine batch sizes in production. This, however, typically leads to batch sizes that are too high. According to (Wild 2002), batch sizes that minimize actual costs are in the region of 60% of EOQ (see Section 9.10).

The development and implementation of multi-echelon inventory models can be time- and resource-consuming, and it requires technical knowledge. While ever more user-friendly systems have mitigated such issues recently, more strategic, organizational and human challenges of implementing systems across several plants and supply chain levels remain (see for example Hieber 2002).

In which problem situations?

Generally speaking, inventory models are useful when the decisions to be made critically affect inventory. Their main application area is therefore obviously inventory management. For a more specific assessment of the use of inventory theory in inventory management, the reader is referred to Section 9.10. Typical inventory management decisions, such as replenishment lot sizes, frequently also affect decisions related to transportation and production. So, indirectly, inventory theory supports these functions as well.

The next section summarizes and compares some of the key aspects of the four OR techniques introduced.

5.4 Comparison of techniques along key characteristics

The previous section defined and discussed the four OR techniques frequently used to support manufacturing logistics in practice. In order to further present, compare and highlight the differences between them, the idea of paradigms, introduced by Kuhn (1970), is useful. A paradigm can be considered as a set of philosophical assumptions that define the nature of possible research and intervention (Mingers and Brocklesby 1997). Paradigms cover aspects such as ontology (what is assumed to exist), epistemology (the nature of valid knowledge), ethics or axiology (what is valued or considered right) and methodology (Mingers 2003).

Mingers (2003) uses such paradigmatic elements to characterize and compare different systems methodologies, with the purpose to help selecting appropriate ones. While he distinguishes between mathematical programming and discrete-event simulation, the remaining methodologies he considers are qualitative, from the field of 'soft' OR (see Section 4.4). A similar exercise is, however, justified for other quantitative techniques as well, since they are popular and frequently used in practice (more frequently than 'soft OR', see Munro and Mingers 2002). Ormerod (2005) made similar observations concerning Mingers' characterization (2003): 'It is difficult to understand why, in a guide for practitioners, the seldom-used soft methods should be favoured both over the much-used hard methods such as statistics and forecasting and over other methods which practitioners apparently do sometimes use, such as decision analysis or scenarios.'

The present section applies Mingers' idea (2003) to the four OR techniques of interest in this thesis. It can be considered as an extension of his work in the sense that a more detailed classification of quantitative techniques is employed. The following six dimensions are used to characterize them:

- 'What it does': A general description of what the technique does, rather than how or why (which is covered in later dimensions). This description helps inferring the ontological and epistemological assumptions covered in the next dimensions.
- Ontology: The things seen, the 'view'. A description of the kinds of things that are taken to have existence and that the technique makes a model of. Each technique focuses on certain aspects of the real system and ignores others.
- Epistemology: What is considered as knowledge. It is here expressed as the way reality (the ontology) is represented, i.e. the elements the model consists of.
- Purpose: The 'why'. The specific question(s) the decision-maker gets help with if this technique is used.
- Solution procedure: The way answers are obtained to the questions addressed (previous dimension). See Section 4.3 for common types of solution procedures.
- Software systems: The types of software systems that are used to implement the models, as well as the standard software systems that make use of them.

The first four dimensions are taken directly from Mingers (2003). To these are added solution procedures and software systems, as they also characterize the different techniques and define their nature of intervention.

Table 5-3 shows the results from describing the four techniques along these six dimensions. For mathematical programming and discrete-event simulation, Mingers' work could be used as a starting point for some of the cells. The researcher used his knowledge about OR techniques to fill in the remaining ones. Usually, it was possible to be more specific for inventory theory than for example deterministic optimization. This is because deterministic optimization is a much broader, more general technique than inventory theory. Other wordings in the cells are certainly possible; discussing and improving them presents an interesting path for further research. Nevertheless, the characterization highlights the differences between the techniques and provides a summary of how each of them can support decision-making.

Table 5-3: A characterization of the main OR techniques used to support manufacturing logistics

	Deterministic optimization	Discrete-event simulation	Queuing theory	Inventory theory
What it does	Model the relationship between many variables using linear and non-linear equations; optimize the value of an objective function within the limits of constraints.	Model the behaviour of entities and activities using variables and logical expressions; imitate the flow of these entities within and between the activities in a visual animation.	Model the steady-state behaviour of entities within and between activities using variables and functions.	Model the relationship between material flows and inventories; calculate inventory levels balancing cost and service performance measures.
Ontology (what is assumed to exist, the 'view')	Systems. Relations between the measurable attributes of entities and processes in the system, together with explicit objectives and constraints.	Processes, queuing systems. Entities and activities with stable patterns of statistical behaviour that form inter-linked processes. Queues of entities between activities.	Processes, queuing systems. Entities and activities with stable patterns of statistical behaviour that form inter-linked processes. Queues of entities between activities.	Systems consisting of flows and inventories of physical entities. Relations between measurable attributes of inventories, entities and replenishments/withdrawals (entities entering/leaving the inventories).
Epistemology (how it is represented)	Decision variables and deterministic parameters, objective function, constraints. Linear and non-linear functions, equations and inequalities.	Deterministic and stochastic variables and logical expressions describing parts of the behaviour of the queuing system. Animated computer visualizations.	Deterministic and stochastic variables linked by formulae that describe the relations and steady-state behaviour of the queuing system.	Deterministic and stochastic variables and functions relating inventory to cost and service performance measures.
Questions addressed (the purpose dimension)	How can the objective be achieved while respecting the constraints?	How does the system perform if it is designed and controlled in a certain way?	How long are the queues, what are the waiting times, resource utilisation, throughput, capacity requirements?	When should inventory replenishment orders be placed and how much should be ordered? Which locations should keep inventory and how much?
Solution procedures	Numerous types of heuristic and optimal algorithms. Simplex algorithm for linear programs.	Descriptive technique. What-if analysis; simulation optimization.	Often descriptive formulae; what-if analysis; for some models, solution algorithms have been developed.	Closed-form solutions for simple cases; various types of heuristic and optimal algorithms. Dynamic programming.
Software systems	General-purpose optimization packages; programming languages; spreadsheets; location software; APS systems	More or less general visual interactive modelling systems; programming languages; spreadsheets	Queuing software systems; spreadsheets; Matematica	Inventory management systems; multi-echelon systems; spreadsheets

5.5 Assessment of classification

The previous sections presented a classification of OR techniques used to support manufacturing logistics. This classification is now assessed along the criteria identified in Section 5.1.

Criterion 1: The classification should highlight the OR techniques that are used in practice to support manufacturing logistics.

Table 5-4 shows how many times each of the techniques was used in the OR applications described in *Interfaces*. This finding has provided the empirical foundation for the proposed classification.

Table 5-4: OR technique usage in manufacturing logistics (*Interfaces* survey)

OR technique	Number of times used
Deterministic optimization	70
Discrete-event simulation	29
Inventory theory	19
Queuing theory	14
Miscellaneous	6

It must be emphasized that the above justification should not be confused with theory testing because it is based on the same data set as was used to develop the classification. It simply shows that the proposed classification indeed finds support in the original data set.

On the other hand, some theory testing is possible by means of other surveys. The high number of discrete-event simulation applications in manufacturing logistics presented at *Winter Simulation Conferences* (51 during four years) provides evidence of the applicability of discrete-event simulation. As far as surveys carried out by other researchers are concerned, few investigated technique usage specifically for areas related to manufacturing logistics. Among the ones that did, most had the methodological weaknesses outlined in Section 5.2, which made comparisons difficult.

Nevertheless, some relevant information can be extracted from the surveys by Fortuin and Zijlstra (2000, 1989). They studied OR applications carried out by a Dutch OR group, most of them within the scope of manufacturing logistics. The 1989 survey included 188 OR applications between 1981 and 1988; the 2000 survey 160 OR applications between 1988 and 1996. Their classification of OR techniques could with minor changes be adapted to the one proposed in this thesis, with the results (in %) shown in Table 5-5.

Table 5-5: OR technique usage in manufacturing logistics (Surveys by Fortuin and Zijlstra 2000, 1989)

OR technique	1989 survey	2000 survey
Deterministic optimization	20	31
Discrete-event simulation	30	14
Inventory theory and queuing theory	41	47
Miscellaneous	9	8

Besides, the recent study by Jahangirian et al. (2010) confirms that discrete-event simulation is the most frequently used simulation technique in manufacturing and business. Note that these authors identified system dynamics as the second most popular technique (32 real-world application papers, compared to 52 on discrete-event simulation). However, almost all the system dynamics papers concern high-level decisions outside the field of manufacturing logistics, such as business policy and strategy development.

Since these surveys were not considered when developing the classification, their use here can be considered as theory testing. As Table 5-5 clearly shows, they support the claim that the proposed classification highlights the main OR techniques used to support manufacturing logistics in practice. In conclusion, there is considerable evidence suggesting that criterion 1 is satisfied.

Criterion 2: The different classes should be mutually exclusive and so clearly defined that most models can be classified easily.

Classifying complex items such as OR models is not easy, and it will normally be possible to find cases of doubt. Section 5.3 provided detailed descriptions of the scope of each technique. Several cases of doubt, for example where to classify a deterministic, normative inventory model, have been treated specifically. Classifying the models described in *Interfaces* provided vast opportunities to test and refine the classification. The final version proved satisfactorily robust, in the sense that most models could be classified easily. Criterion 2 is thus considered as satisfied as well.

Criterion 3: The different techniques should have different world views, be practised by different people and implemented in different types of software systems.

The comparison in the previous section highlights the paradigmatic differences between the four techniques. For example, deterministic optimization and inventory theory model systems, discrete-event simulation and queuing theory model processes in these systems. Deterministic optimization is normative, discrete-event simulation descriptive. Etc. Other researchers have noted the paradigmatic difference between these OR techniques. De Kok et al. (2005) stress it for optimization as opposed to the inventory-theoretic models they use. Mingers (2003) distinguishes ‘mathematical programming’ from ‘visual discrete-event simulation’ when classifying a variety of management science methods according to their philosophical assumptions.

The techniques distinguished are in the researcher’s experience also often practiced by different experts. That is, each of these classes has its own group of adepts and advocates.

This is, for example, manifested by different groups of authors contributing to the respective techniques' research literature. For example, authors like Suri et al. (1995), De Treville and van Ackere (2006), Gershwin (1994) and Buzacott and Shanthikumar (1993) concentrate on queuing theory. It is also reflected by the frequent discussions and sometimes even arguments between advocates of different techniques. For example, there has been competition between optimization and discrete-event simulation for decades (Powell 2005, Mentzer 1989).

Finally, the different techniques are also implemented in different types of software systems, as explained in the previous sections. In conclusion, this chapter provides ample support that criterion 3 is satisfied.

Criterion 4: The classification should use common and established terms and definitions.

Most operations researchers would agree on the meaning of the terms deterministic optimization, discrete-event simulation, queuing theory and inventory theory. This can for example be seen in most OR textbooks, that have separate chapters for each of these techniques (although deterministic optimization is usually separated into subclasses such as linear and integer programming). See for example Winston (2004). Standard definitions are used for optimization (Rardin 1998) and discrete-event simulation (Robinson 2004); the scope of inventory theory and queuing theory is also fairly standard. Thus, criterion 4 is considered as satisfied as well.

In conclusion, the proposed classification is considered to satisfy the criteria set out.

5.6 Summary

In order to provide an understanding of the main OR techniques used in practice to support manufacturing logistics, this chapter has defined and characterized deterministic optimization, discrete-event simulation, queuing theory and inventory theory. These techniques differ in the way they abstract the real-world system, the questions they address, the way they provide answers and the software systems they are implemented in. They have different strengths and weaknesses, and are applicable in different problem situations.

Such characterizations are crucial to understand the applicability of these OR techniques in manufacturing logistics, and they contribute to this thesis' overall objective. However, they are not sufficient, for the following reasons:

- They are mostly descriptive, i.e. they describe the characteristics of each technique, but do not explain in which situations they are particularly valuable (Some such statements could be made, but only at a very general and superficial level). This weakness was already stressed for research addressing the applicability of OR in general (Section 4.15). The knowledge reviewed and developed so far pays limited attention to relating technique applicability to problem situation characteristics, even though this is needed to provide concrete rules on when to use each technique.
- Statements about when to use a technique are often made assuming that some OR technique *will* be used. That is, the 'when' is made in comparison to other OR techniques. Relatively little is said about which problem situations, among all manufacturing logistics problem situations, can benefit from OR techniques. For example, discrete-event simulation is said to be useful if there are few choices (see above). However, not *all* decisions with few choices can benefit from discrete-event simulation. Often, a qualitative approach or a spreadsheet will be sufficient.

The remainder of this thesis therefore focuses on characterizing the problem situations that can benefit from the different OR techniques. By restricting the scope to manufacturing logistics, much more specific statements can be made about the problem situations characteristics that make OR techniques a good choice. The next chapter makes a step in this direction by highlighting the types of manufacturing logistics decisions supported by OR.

6 Decisions supported by OR techniques

This chapter proposes a classification of manufacturing logistics decisions supported by OR. The chapter has a structure similar to the one in the previous chapter. First, the purpose of such a classification is explained and detailed criteria specified that it has to satisfy. Next, relevant previous literature is reviewed and assessed. The third section describes how the classification was developed, as well as the classification itself, with detailed descriptions of each class. Its quality is then checked by means of the criteria developed in the first section. The chapter concludes that the developed classification contributes to the overall objective of this thesis, but stresses the need for more detailed characterizations of the problem situations that can benefit from the various OR techniques.

The main contribution of this chapter is thus the classification in Figure 6-1, which highlights the main decision types supported by from OR.

6.1 Purpose

The classification's precise purpose is to allow rigorous classification of OR applications in manufacturing logistics. It should highlight the decision types supported by OR techniques and provide a purposeful basis for research on the applicability of OR techniques in manufacturing logistics, such as the one carried out in subsequent chapters.

In order to achieve these goals, the classification needs to satisfy the following criteria:

- (1) Its scope should be manufacturing logistics.
- (2) It should allow clear classification of OR applications, and highlight the decision types frequently supported by such applications.
- (3) It should be based on well-known, established frameworks.

Criterion (1) and (2) are required in order to address this thesis' scope and objective. Criterion (3) should simplify acceptance and agreement by other researchers and practitioners. The next section reviews relevant existing literature.

6.2 Literature review

Journal articles and academic textbooks in the areas of operations and production management, logistics and supply chain management were reviewed in order to identify existing frameworks and classifications that would meet the above criteria.

The following types of relevant research were thereby identified:

- i) Manufacturing planning and control (MPC) system frameworks, such as presented in Arnold et al. (2008), Vollmann et al. (2005) and Hopp and Spearman (2001).
- ii) Frameworks of tasks and processes in logistics and supply chain management and related fields, such as presented by Simchi-Levi et al. (2008), Jonsson (2008) and Fleischmann et al. (2005).
- iii) Classifications used to classify research and OR applications in operations management and related fields, such as in Jahangirian et al. (2010), Shafer and Smunt

(2004), Fortuin and Zijlstra (2000, 1989), Pannirselvam et al. (1999) and Ford et al. (1987).

In general, the review revealed a plethora of more and less well-defined and well-known frameworks, reference models and classifications. Nevertheless, it also revealed a lack of common terminology and concepts. For example, even the term ‘business process’ has countless different definitions, as was already observed by Melao and Pidd (2003). Moreover, especially type (iii) research is often not clear and detailed enough for classificatory purposes. The main problems with type (i) and (ii) frameworks are that they only cover parts of all manufacturing logistics decisions, and that it is often not easy to classify OR applications according to their structure.

Thus, there is a research gap in identifying a classification of manufacturing logistics decisions that permits to clearly classify OR applications. This chapter aims to fill this gap by developing a well-defined, purposeful classification which is based on well-known, established frameworks from the literature.

At the end of Chapter 3, four such well-known frameworks were reviewed in order to characterize typical activities/decisions in manufacturing logistics. It was also argued that they provided particularly good starting points for the classification to be developed here. These frameworks are therefore now assessed in more detail according to the three criteria set in the previous section. Since they are presented in popular, well-cited academic textbooks, criterion (3) is considered as satisfied, so focus is on criteria (1) and (2).

MPC system frameworks (Vollmann et al. 2005, Hopp and Spearman 2001)

Criterion (1): The scope of the MPC system frameworks is too narrow. They focus on control issues, only marginally addressing activities related to the structure of the manufacturing system. Moreover, they ignore more strategic tasks related to control, for example selecting appropriate control systems and principles. Furthermore, focus is on production, and activities such as inventory and transportation management are not explicitly included. Activities involving several plants and organizations are also missing, as Vollmann et al. (2005) remark themselves. Examples of such activities include vendor managed inventory (see Simchi-Levi et al. 2008 for details) and coordinated mid-term production and capacity planning.

Criterion (2): Vollmann et al. (2005) group decisions according to the division of modules in ERP systems, which are built around the traditional Material Requirements Planning (MRP) approach to planning (see Orlicky 1975 for details). Such a division does not appropriately reflect the decision types supported by OR. For example, material planning and capacity planning are separate modules in ERP systems because these two tasks are carried out separately in the traditional MRP planning approach. In optimization models, however, capacity constraints can be considered directly when a material plan is developed, so material and capacity planning should belong to the same decision type. A second example concerns OR models supporting tactical production planning, often called aggregate planning models (Chopra and Meindl 2007) or master planning models (Rohde and Wagner 2005). Such models fall most appropriately within the sales and operations planning category of Vollmann’s (2005) MPC framework. However, it can be misleading to state that such models support sales and operations planning, as they really only help establishing the production and inventory portion of the sales and operations plan. Hopp and Spearman’s (2001) pull planning framework has the advantage that it is less influenced by MRP thinking and better

adapted to pull systems. The specifics of pull systems, however, make the framework less suitable for classification of manufacturing logistics decisions in general.

Thus, the MPC frameworks have a scope that is too narrow, and their groupings of activities/decisions do not well enough reflect the decisions supported by OR.

IT capabilities for supply chain excellence (Simchi-Levi et al. 2008)

Criterion (1): This framework is quite comprehensive when it comes to manufacturing logistics decisions involving several plants or companies. They range from strategic to operational and address structural as well as control-related issues. On the other hand, activities concerning a single unit or plant are not paid enough attention to, for example production plant design.

Criterion (2): This framework includes decisions supported by both *analytical* and *transactional* IT. Transactional IT is mainly reflected by the *operational execution* layer. The remaining layers concern analytical IT, so they highlight decisions supported by OR techniques (see Section 4.7).

Thus, the three layers *strategic network design*, *tactical planning* and *operational planning* of this framework make a good step into the right direction, highlighting decision types supported by OR. They need, however, to be complemented by OR-supported decisions at the unit/plant level.

Supply Chain Planning Matrix (Fleischmann et al. 2005)

Criterion (1): The scope of the Supply Chain Planning Matrix is the widest of the frameworks reviewed. It includes both structural and control-related issues, ranges from strategic down to operational decisions, covers all the different logistics system scopes defined in Subsection 3.2.3 and includes the main functional areas of importance for logistics, such as inventory, transportation and production. In fact, its scope even surpasses manufacturing logistics because it includes sales-related activities such as forecasting. They are not considered as manufacturing logistics in this thesis (see Section 3.2).

Criterion (2): The primary purpose of the Supply Chain Planning Matrix is to show the typical tasks occurring in most supply chains (Fleischmann et al. 2005). Even though it is related to the typical modular structure of APS systems (see Section 4.7), the grouping and terminology in the matrix only partially reflects the decisions supported by OR. Certain tasks are included even though they do not seem to be frequently supported by OR, such as planning and evaluation of cooperations (see Subsection 7.4.1). Moreover, certain typical OR-supported decisions, such as master planning (see Table 6-2 on page 125), are missing in the matrix. It would not be fully appropriate to consider master planning as a part of *master production scheduling*, since the former uses product groups, the latter is at the end-item level (Vollmann et al. 2005).

Thus, the Supply Chain Planning Matrix provides an adequate structure, but its content needs to be adjusted to better reflect the decisions actually supported by OR techniques.

Table 6-1: This table summarizes how well frameworks in the literature fit the requirements for a classification of typical OR-supported manufacturing logistics decisions. The requirements are expressed in terms of the two criteria identified at the beginning of this chapter.

	Scope (criterion 1)	Classifying/reflecting/high-lighting ... (criterion 2)
<i>Classification of manufacturing logistics decisions supported by OR</i>	<i>Manufacturing logistics</i>	<i>Decisions supported by OR</i>
Vollmann et al. (2005)	Operational/tactical control-related decisions in production	Modules in ERP systems
Hopp and Spearman (2001)	Operational/tactical control-related decisions in production	Typical activities in pull systems
Simchi-Levi et al. (2008)	Structural and control-related decisions crossing plants and organizations	Tasks supported by transactional and analytical IT
Fleischmann et al. (2005)	Manufacturing logistics and sales	Tasks occurring in most supply chain types

Table 6-1 summarizes this section's discussion. As can be seen, the Supply Chain Planning Matrix (Fleischmann et al. 2005) best satisfies criterion (1), Simchi-Levi et al.'s (2008) framework provides the best fit in terms of criterion (2). These two frameworks therefore provided crucial input to the classification introduced in the next section.

6.3 The classification

This section formulates a classification of manufacturing logistics decisions that satisfies the criteria specified at the beginning of this chapter.

The actual process of developing the classification started from the frameworks reviewed in the previous section. The OR applications included in the survey of the *Interfaces* journal and the *Winter Simulation Conference* proceedings (see Chapter 7) were scrutinized in order to identify the types of decisions actually supported by OR (criterion 2). This was done in a highly iterative process between studying OR applications and updating/combining the reviewed frameworks, with the goal to work out detailed classes of relevant decisions that satisfied the criteria. As in the previous chapter, the process was inductive, similar to elements of grounded analysis/theory (Easterby-Smith et al. 2002, Strauss and Corbin 1998).

This resulted in a classification with seven classes (Figure 6-1). As can be seen, its structure resembles the Supply Chain Planning Matrix. The main structural changes are as follows:

- The *supply chain process* dimension procurement-production-distribution-sales is replaced by a *function* dimension inventory-production-transportation. OR models in procurement and distribution usually address issues related to inventory and transportation, so the new terminology better reflects the functions and decisions actually addressed by OR models. It is also the terminology used in the operational planning layer of Simchi-Levi et al.'s (2008) 'IT capabilities for supply chain excellence' framework.
- The *sales* process is removed as it is not considered as logistics itself (see Section 3.2).

The main aim with the grouping and terminology inside the classification is to satisfy criteria (2) and (3). Five of the seven classes come from the strategic, tactical and operational layers in Simchi-Levi et al.'s framework. There was a need to add two decision types, *production plant design* and *determination of production rules and policies* in order to make the classification complete. As the next section will show, these decision types are also frequently supported by OR. They lack in Simchi-Levi et al.'s framework, presumably because these authors focus on decisions at the supply chain level.

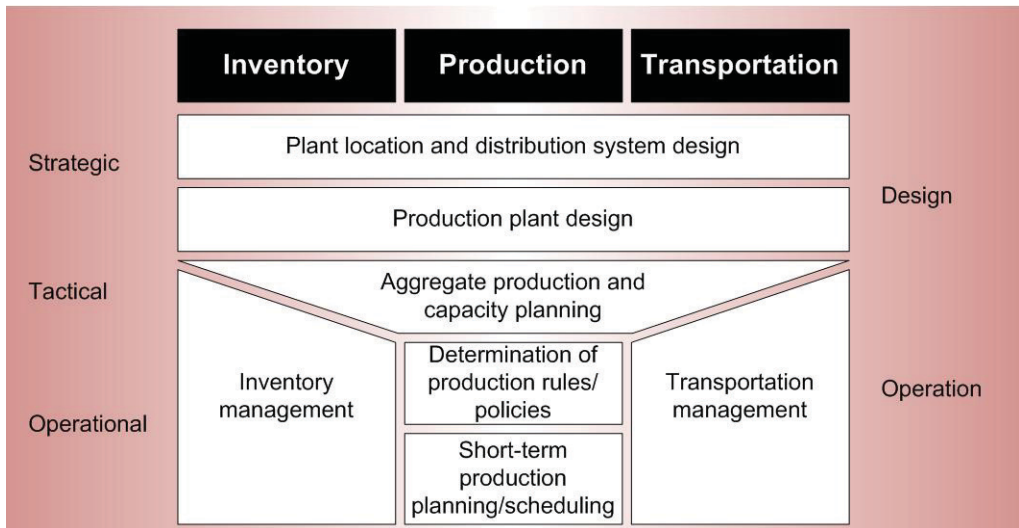


Figure 6-1: The manufacturing logistics decision types frequently supported by OR

Each class is now presented in detail by explaining the decisions associated with it. The next section will assess the classification along the three criteria initially set out.

(1) Plant location and distribution system design

This decision type is concerned with long-term decisions related to the structure (and control) of the supply chain. Given product and market characteristics, the goal is to design or redesign the entire network from suppliers to production plants to distribution facilities, such as to fulfil demand at lowest total cost. Typical decisions include plant and warehouse locations and capacities, transportation mode selection, transportation outsourcing decisions and strategic carrier selection, distributor selection and fleet design. Moreover, they concern aggregate material flows from suppliers to production plants to warehouses and finally to customers, i.e., which plants to supply from which suppliers, which warehouses to supply from which plants, and which customers to supply from which warehouses. A critical decision is, for example, whether to use centralized or local plants and warehouses (see Simchi-Levi et al. 2008). A related question is at which plants to carry out which processes. Plant location and distribution system design needs to take into consideration inventory, production and transportation, and it heavily affects how effectively these functions can be operated. For further details, see Simchi-Levi et al. (2008) and Goetschalckx and Fleischmann (2005).

(2) Production plant design

Production plant design is the second strategic decision type frequently supported by OR. While the first type addresses the supply chain with plants and material flows between them, production plant design considers strategic issues within the four walls of a single plant. It involves physically organizing a single production plant, i.e. designing the layout of the plant and the resulting material flows between the machines. It determines the required number and capacities of physical resources, their locations and the tasks they have to carry out. Such resources include machines and workstations, operators, buffers, material handling devices and other equipment. In manufacturing lines, for example, an important issue is line balancing, i.e. assigning tasks (individual work elements) to a series of linked workstations. Layout decisions also often involve assigning departments to locations within the plant. While most of the issues addressed within production plant design are of strategic character, there are tactical issues as well (for example staffing policies). Production plant design concerns both inventory-, production- and transportation-related issues, and it heavily affects how effectively these functions can be carried out. Further details can typically be found in operations management textbooks, such as Hill (Hill 2005) and Hanna and Newman (2001).

(3) Aggregate production and capacity planning

Aggregate production and capacity planning deals with tactical production and capacity decisions. It determines the best way to meet forecast demand by adjusting regular and overtime production rates, inventory levels, labour levels, subcontracting and backordering rates and other controllable variables. It assures efficient utilization of available capacities and determines capacity expansions and the build-up of seasonal stock. Aggregate production and capacity planning has time horizons from 6–18 months and weekly or monthly time buckets (periods). Chopra and Meindl (2007) provide further details on aggregate production and capacity planning at a single plant. When a supply chain consisting of several plants is considered, aggregate production and capacity planning is sometimes called *supply chain master planning* (Rohde and Wagner 2005). It synchronizes the flow of materials along the entire supply chain, determining how much of each product group to produce, assemble, package and store at each plant, and how much to transport between plants. In terms of Vollmann et al.'s (2005) framework, this decision type is best characterized as part of sales and operations planning, in as much as it coordinates different functions (supply, inventory, production, transportation) and develops an aggregate mid-term company plan. It does, however, not cover all aspects of a typical sales and operations planning process.

(4) Determination of production rules/policies

This decision type takes the physical structure of the inside of a plant as given and concerns tactical evaluation and selection of production rules and policies. In manufacturing lines, work-in-process levels are to be determined. In batch production, tactical lot sizing is an issue, as well as cyclic scheduling. This class of decisions also includes determination of procedures for detailed scheduling and sequencing. In Just-in-time systems using KANBAN cards, the number of cards and the quantity to be produced per card are to be determined. A similar issue is determining the number of pallets and batch sizes in manufacturing cells, or – more generally – determining work-in-process levels in closed-loop systems. In process-based production, rules are needed to determine when to switch production to a different product, and to determine to which product to switch. The horizon of such decisions is typically shorter than production plant design, but longer than short-term production

planning/scheduling. For further details on such issues, see for example Hopp and Spearman (2001).

(5) Inventory management

This class covers tactical and operational inventory management decisions. The goal of such decisions is to meet service level targets at lowest total cost. Tactical decisions concern the mechanisms and approaches to control inventories of raw material, component and finished-goods. Key issues include safety stock quantities, reorder points, reorder quantities and review cycle times. In multi-stage supply chains with stock locations at several vertical echelons (such as before packing, after packing and at distribution centres), an important decision is where to keep how much safety stock such that supply-chain-wide costs are minimized while a certain level of product availability to the external customer is kept. Postponement/speculation and risk pooling are related issues. Operational, short-term inventory decisions are concerned with actual replenishment times and quantities, as well as daily/weekly setting of parameters such as safety stocks. For further details, see Simchi-Levi et al. (2008) or Silver et al. (1998).

Note that a number of issues related to inventory control are not covered here because they belong to other decision types. In particular, the build-up of stock ahead of peak-selling periods or for other purposes is part of aggregate production and capacity planning. The size of work-in-process buffers between different production operations within a plant is normally determined by production rules/policies (e.g. KANBAN quantities).

(6) Transportation management

This decision type covers tactical and operational decisions concerning transportation and distribution. The scope of tasks is based on Fleischmann (2005). Tactical decisions are concerned with rules and policies. They determine transportation frequencies and shipment sizes, which are used as target values for short-term decisions on shipment quantities. The selection of distribution paths (parcel service, from distribution centre or from factory) follows often general rules fixed by mid-term decisions. Similar questions have to be addressed also on the procurement side. Operational decisions (deployment) include actual shipment times and quantities, vehicle loading, distribution paths for each individual shipments and handling of exceptional situations such as stock-out. For manufacturing firms owning a transportation fleet, *vehicle routing and scheduling* decisions aim at its optimal operational use given customer service requirements. Decisions include the assignment of customer orders to vehicles, the sequence that a vehicle services the customers assigned to it, and the actual time schedules of the vehicles. For some more details see Fleischmann (2005).

As for inventory management, several transportation management-related issues are addressed within the context of other decision types. Plant location and distribution system design allocates plants to customers, thereby determining aggregate transportation quantities between plants and customers. Strategic transportation mode selection, transportation outsourcing, carrier selection and fleet design are also covered there. In aggregate production and capacity planning, aggregate (for example monthly) transport quantities from suppliers and between plants/warehouses are determined. Transportation within the four walls of a production plant is addressed by production plant design and production rules/policies. Thus, the present category concentrates on mid-term policies and short-term deployment of transportation between different supply chain points.

(7) Short-term production planning/scheduling

This decision type, finally, concerns operational, short-term decisions about how much to produce of what, when, and by which resources, given resources and external demand requirements. Often, such decisions result in time-phased plans/schedules (The terms plan and schedule are used interchangeably). Such plans/schedules have short planning horizons, such as a day or a week. Accordingly, time periods used are typically hours, shifts or days. Although their scope is often limited to a single plant, they can also concern short-term coordination of multi-plant networks. Shop-floor control of production activities constitutes a further element within this decision type. For further information, see McKay and Wiers (2004).

6.4 Assessment of classification

The previous section proposed seven classes of manufacturing logistics decisions, collectively covering the majority of OR applications in manufacturing logistics. This classification is now assessed along the criteria identified at the beginning of this chapter.

Criterion 1: Its scope should be manufacturing logistics.

As Figure 6-1 shows, it spans across all planning horizons and logistics system scopes. It includes design and operation, and it covers inventory, production and transportation. Thus, it comprehensively covers the field of manufacturing logistics.

Criterion 2: It should allow clear classification of OR applications, and highlight the decision types frequently supported by such applications.

This is the most important criterion to be validated. The proposed classification was developed based on close to 200 OR applications described in *Interfaces* and the *Winter Simulation Conference* proceedings. The detailed descriptions provided in the previous section allowed clear classification of most of them, and it is the researcher's contention that the seven classes well highlight which decisions were actually supported. Thus, though classifying complex items such as manufacturing logistics decisions is not always easy and it will normally be possible to find cases of doubt, the proposed classification has proven sufficiently robust.

Table 6-2 shows that most of the OR applications described in *Interfaces* and the *Winter Simulation Conference* proceedings addressed decisions of the seven types distinguished by the classification; few had to be classified as 'miscellaneous'. This provides substantial empirical evidence that the classification fulfils its purpose of highlighting OR-supported decisions.

Table 6-2: This table shows the number of OR applications per decision type, based on the survey of *Interfaces* and the *Winter Simulation Conference* proceedings presented in the next chapter.

Decision type	<i>Interfaces</i> survey	<i>Winter Simulation</i> survey
Plant location and distribution system design	21	2
Production plant design	16	26
Aggregate production and capacity planning	12	0
Determination of production rules/policies	10	26
Transportation management	5	1
Inventory management	16	5
Short-term production planning/scheduling	30	7
Miscellaneous	6	1

These results will be discussed in detail in the next chapter. Here, they are shown in order to provide empirical evidence that criterion (2) is satisfied. As in the previous chapter, it must be emphasized that the above justification should not be confused with theory testing because it is based on the same data set as was used to develop the classification. It simply shows that the proposed classification indeed finds support in the original data set.

Surveys carried out by other researchers only provide limited opportunity for theory testing. Few distinguished between different decision types within manufacturing logistics, and the ones that did, date many years back, had low response rates and used different terminology and classifications.

The studies by Fortuin and Zijlstra (2000, 1989) make an exception. Based on a survey of several hundred OR applications, most of them in manufacturing logistics, they developed a grouping of decisions into application areas and counted the number of applications per area (Table 6-3). While somewhat less detailed, their grouping of manufacturing logistics decisions is similar to the one proposed in this thesis, in the sense that corresponding classes could be identified easily. This is done in Table 6-3. As the table also shows, most of the applications they surveyed belong to the proposed seven decision types. Thus, these authors' results largely agree with the present study, thereby providing some additional empirical support.

The five surveys reviewed by Ford et al. (1987) should also be mentioned, even though they date many years back and had low response rates. They distinguished between the manufacturing logistics areas scheduling, production control, inventory analysis/control, plant layout, logistics (transportation) and plant location, and they found regular OR usage in all of them. Their areas are easily associated with corresponding decision types as proposed in this thesis, providing some additional empirical support.

Table 6-3: Types of decisions supported by the Dutch OR group surveyed by Fortuin and Zijlstra (2000, 1989)

Application areas distinguished by Fortuin and Zijlstra	1989 survey	2000 survey	Corresponding decision types in this thesis
Production planning, production control, production location, production allocation	30	22	1,3,4,7
Design of production systems and machines, including transport during production	33	28	2
Transport and storage of finished products, their physical distribution, service after sales and repair	14	27	5,6
Design of transport systems and warehouses for finished products	3	0	
Performance analysis of computer systems and communication systems	5	3	
Education and training: courses, instruction	7	6	
Miscellaneous	8	14	

In conclusion, there is considerable evidence that criterion (2) is satisfied.

Criterion 3: It should be based on well-known, established frameworks.

The main starting points for developing the classification were Fleischmann et al.'s (2005) Supply Chain Planning Matrix and Simchi-Levi et al.'s (2008) 'IT capabilities for supply chain excellence' framework. The latter is presented in one of the most well-known, popular textbooks in logistics and supply chain management; the former is based on the structure of APS systems known in both industry and academia. Criterion 3 is thus also considered as fulfilled.

In conclusion, the proposed classification is considered to satisfy the criteria set out.

6.5 Summary

This chapter has proposed a classification of manufacturing logistics decisions supported by OR. It consists of the seven decision types highlighted in Figure 6-1. Several surveys of OR applications provide empirical evidence that most OR applications fall into the seven classes distinguished.

This classification provides a first, very rough understanding of the problem situations in which OR techniques tend to work well. However, it does not provide enough details about the characteristics of these problem situations. For example, not all plant location questions call for an OR model. Similarly, OR might not be the right approach to production scheduling in all situation. Moreover, problem situation characteristics affect the choice of OR techniques, i.e. different techniques are suitable in different situations. A distinction between OR techniques should be therefore made. The remainder of this thesis builds upon the present chapter by investigating, in more detail, the problem situations that have benefitted from OR, and which OR techniques were used.

		OR technique			
		Deterministic optimization	Discrete-event simulation	Queuing theory	Inventory theory
Decision type	Short-term production planning/scheduling				
	Plant location and distribution system design				
	Production plant design				
	Inventory management				
	Aggregate production and capacity planning				
	Determination of production rules/policies				
	Transportation management				

Figure 6-2: Framework highlighting manufacturing logistics decision types supported by OR as well as the main OR techniques used

Figure 6-2 combines the two classifications proposed in this part into the decision-technique matrix, constituting a framework highlighting manufacturing logistics decision types supported by OR as well as the OR techniques mainly used. It provides an overall structure to study and discuss the applicability of OR techniques in manufacturing logistics. It will be used in the next chapters. In particular, it provides the overall structure for the guidelines presented in Chapter 9.

PART IV – EMPIRICAL INVESTIGATIONS: WHICH PROBLEM SITUATIONS ARE SUPPORTED BY WHICH OR TECHNIQUES?

This part presents the main empirical investigations carried out as a part of this thesis, which aimed at a better understanding of the problem situations supported by OR, as well of as the link between these problem situations and the different OR techniques' applicability. It corresponds to the second specific objective defined in the introduction of this thesis: Providing substantial empirical evidence of the type of problem situations that can benefit from the different OR techniques.

Empirical data has been obtained by looking at *successful past OR applications*. That is, by asking 'In which situations have OR techniques worked before?' The advantage of studying past cases is precisely that it provides empirical evidence, as opposed to claims made by subject experts. This evidence can be used to validate the experts' claims, which is important. Murphy (2005a, 2005b, 2005c) further motivates this research approach, asking for surveys of OR applications. Littlechild and Shutler (1991, p. 266) also support it by remarking that a study of past case histories can help speed up the acquisition of experience and of the art of OR problem-solving, which is required to select appropriate techniques.

It is important to be aware, however, that the approach chosen assumes the study of successful past cases to provide a good means to investigate OR applicability. It ignores that research and development can lead to novel opportunities. For example, recent theoretical developments in stochastic programming (a subfield of optimization) can lead to increased use of this technique in the future. This weakness is further discussed within the context of this thesis' limitations (Subsection 10.4.2). The result of the present study can thus be considered as a *state-of-the-art* of the practice of OR in manufacturing logistics.

In this thesis, information about past OR applications comes from two main sources:

1. OR applications documented in literature. Research literature contains a large number of application papers, and they normally contain a detailed description of the problem situation addressed and the OR technique used. Such literature has therefore been systematically surveyed and relevant information extracted and presented as survey results. Close to 200 OR applications have been studied this way. This research activity and its main results are presented in Chapter 7. Discussion of the results is also partially covered in this chapter, and completed as a part of the guidelines in Chapter 9. Note that, even though this survey activity is based on literature, it provides *empirical* data since it collects information about real-world OR applications (with secondary data sources).
2. Three case studies for additional in-depth understanding. The case studies are meant as a follow-up to the surveys, providing even more detailed insights into the situations in which OR techniques can be beneficial. The advantage of case studies is that they allow explicit consideration of many contextual details. The case study activity is presented in Chapter 8, including methodology, case descriptions and a preliminary analysis. The remainder of the analysis is incorporated in the guidelines in Chapter 9.

Thus, the OR applications studied in this part IV also provide crucial input to the development of the guidelines on the applicability of OR techniques presented in Chapter 9.

7 Surveys

This chapter presents one of the key activities of this thesis: Two extensive surveys of OR applications described in the literature, investigating the link between problem situation characteristics and OR technique usage.

First, the literature is reviewed in order to identify problem situation characteristics that are likely to affect the applicability of OR techniques. These characteristics define the ‘survey questions’, i.e. the specific issues investigated in each of the surveyed OR applications. The second section presents an overview of other researchers’ surveys that investigated some of the identified characteristics; they will be taken up again in the discussion of this thesis’ surveys. Section three provides details about methodological choices and argues for them. Section four is the most important: It shows the main survey results and discusses many of them. The remainder of the discussion is most naturally incorporated in Chapter 9 in order to avoid some repetition. Section five summarizes key results and presents implications.

7.1 *Problem situation characteristics studied*

As explained in Section 4.11, the problem situation is a key factor determining how appropriate different OR techniques are in a certain context. The problem situation can be described along various characteristics, such as the scope of the logistics system it concerns or the type of industry. Which characteristics are likely to be of importance when determining the appropriateness of different OR techniques?

As a preparation of the survey, the literature was reviewed in order to identify such characteristics. This resulted in the following five characteristics:

- Type of decision
- Planning horizon
- Logistics system scope
- Company size
- Industry

These characteristics will be the ones studied in this thesis’ surveys (the ‘survey questions’). Each of them is now motivated in detail. Other researchers’ claims and findings about the link between them and OR usage/applicability are thereby also briefly reviewed; they will be taken up in more detail when discussing survey results.

Type of decision

This is one of the most frequently used characteristics when assessing the applicability of OR and its techniques. As the following review shows, several researchers have concentrated on one particular decision type and discussed OR technique applicability for it.

Plant location and distribution system design: For this decision type, Laval et al. (2005) and Bookbinder et al. (1989) compared the use of optimization to spreadsheet modelling and concluded that both can provide useful decision support. Ballou and Masters (1999, 1993) found that commercial software systems were often based on linear/mixed-integer programming, but that in practice, simple rule-based approaches were most frequently used.

Production plant design and the determination of production rules/policies: Alden et al. (2006) discuss the applicability of OR techniques for these decision types. They found that queuing theory works for simple, serial lines, discrete-event simulation in more complex contexts. (Suri et al. 1995) also compared these two techniques in this context.

Aggregate production and capacity planning: Buxey (2005) studied how aggregate production and capacity planning was carried out at 42 different production plants. He found that manufacturers select straightforward strategies, mainly ‘chase’, and concludes that OR models/techniques ‘revolve around an eminently plausible but entirely false doctrine’ and therefore are of little use to industry. Ten year earlier, he carried out a similar study and made similar conclusions (Buxey 1995). Nam and Logendran (1992) provided a framework of OR models/techniques addressing this decision type, with the purpose to help determine their suitability given a particular real-world context. They concluded, however, that few of the models and techniques had actually been implemented in practice, and that techniques should be developed that emphasize practical importance.

Short-term production planning/scheduling: A considerable number of researchers discuss the applicability of deterministic optimization for this decision type, for example Gupta and Stafford (2006) and McKay et al. (2002). This issue has attracted particular attention because of a large body of models in the literature which have never been applied in practice. Most studies indicate a significant gap between the results of academic research and scheduling practice.

Administrative process design: Melao and Pidd (2003) investigated the use of discrete-event simulation to support administrative process design and found that it was seldom used for this purpose.

A number of surveys were not limited to one decision type, but investigated which types of decisions were most frequently supported (as was done in the previous chapter). While most of them used broad application areas, such as ‘marketing’ and ‘production’ (see next section), some distinguished between several types of decisions within the scope of manufacturing logistics. Jahangirian et al. (2010) and Shafer and Smunt (2004) focused on simulation application papers and classified relevant papers into 24 and 17 different application areas, respectively. Terzi and Cavalieri (2004), focusing on simulation in the supply chain context, classified relevant publications into different ‘supply chain processes’, such as inventory and transportation. Smith (2003) and the Simulation Study Group (1991) investigated application areas of discrete-event simulation, using several detailed decision types within manufacturing. The application areas distinguished by Fortuin and Zijlstra’s (2000, 1989) were shown in Table 6-3. The two surveys carried out by Ford et al. (1987), finally, distinguished between six manufacturing logistics decision types and investigated the use of seven OR techniques for these decisions. Unfortunately, these surveys date many years back and their response rates were low, so their relevance today is more limited.

Several researchers ask for further studies that investigate the link between decision types and OR techniques (Fildes and Ranyard 1997, Olhager and Rapp 1995). While both references date some years back, there is still a lack of such research today.

In conclusion, there is considerable literature suggesting that the type of decision affects the suitability of OR techniques. It is an important issue and will therefore be given considerable attention in the remainder of this thesis. In particular, the guidelines in Chapter 9 discuss OR applicability separately for each decision type.

Planning horizon

Planning horizon is also a frequently used characteristic when making claims about OR applicability. Ackoff (1987) claimed that the problems suitable for OR tended to be operational and tactical, rather than strategic. Akkermans and Bertrand (1997) also state that OR is mainly used for these planning horizons. Rosenhead and Mingers (2001a) emphasize that most strategic, one-of-a-kind decisions are excluded from OR because of high uncertainty and diverging values and beliefs. Surveys also sometimes investigate OR usage for different planning horizons (Stenfors et al. 2007, Fortuin and Zijlstra 2000, Clark and Scott 1999, Eom et al. 1998, Eom and Lee 1990, Fortuin and Zijlstra 1989). Most of them find that OR is actively used also for strategic purposes. The planning horizon is thus an interesting issue within the context of OR applicability.

Logistics system scope

It is also interesting to study if and how OR applicability depends on the logistics system scope. Looking at Flood and Jackson's (1991)'s System of Systems Methodologies (see Section 4.15), one would expect OR to be less suitable for supply chain decisions because they typically involve various stakeholders with different strategies and interests (pluralist participants). Neely (1993) reviewed some literature and made findings supporting this view. On the other hand, a quick review of the literature reveals that there have been numerous applications of deterministic optimization in supply chains (for example Denton et al. 2006). Also, several studies emphasized the usefulness of discrete-event simulations in supply chains (Kleijnen 2005, Terzi and Cavalieri 2004, Chwif et al. 2002). So there is a need for a more detailed, empirical assessment of OR usage for different system scopes.

Company size

Several researchers identified a positive correlation between company size and extent of OR usage (Stenfors et al. 2007, Fildes and Ranyard 1997, Morgan 1989). Such studies suggest that OR has a higher applicability in large companies than in small companies. Morgan (1989) asks for further studies investigating this link. Most existing studies date some years back, so there is a need to provide up-to-date, empirical evidence.

Industry

Since the characteristics of manufacturing systems differ between industries, it is natural to expect that OR usage does as well. Nevertheless, there is a lack of studies investigating this. Vatter (1967) studied OR use by industry and did not find clear evidence that OR usage was industry-dependent. But this work is 40 years old and the industry classification used was highly aggregated. Morgan (1989) and more recently Murphy (2005a, 2001) asked for further research studying differences in OR activity by industry.

In conclusion, the above five characteristics seem to be of particular relevance when investigating OR technique usage and applicability. The surveys carried out in this thesis, presented in Sections 7.3 and 7.4, therefore concentrate on these five characteristics. Looking at various other characteristics would, however, also be interesting, for example the process type. It opens numerous opportunities for further research.

7.2 Literature review

A key epistemological stance of this thesis is that surveys of OR practice are particularly relevant to provide valid information on OR applicability. This section therefore provides an overview of such surveys carried out by other researchers. Focus is on surveys that

- (1) study real-world OR applications in manufacturing logistics
- (2) address at least one of the five problem situation characteristics identified in the previous section.

The quality and comprehensiveness of other researchers' surveys is assessed, which leads to the conclusion that there is a need for additional surveys. Note that several of the surveys named here were already introduced earlier, in particular in the previous section. The present section provides a structured overview.

Most surveys of OR practice employed questionnaires mailed to industrial organizations or OR practitioners. Typically, such surveys investigated the role and status of OR in industry, the OR techniques frequently used, the common users of OR, reasons for success and failure of OR projects, difficulties encountered etc. They were mainly concerned with the promotion, success and survival of OR as a discipline. Fildes and Ranyard (1997) and Morgan (1989) review and summarize older surveys carried out in the United Kingdom and in the United States, respectively. Similar surveys were also carried out in numerous other countries. Chen and Wei (2002) provide a comprehensive list of references to surveys that investigated the status of OR in countries around the world.

Surveys also regularly asked about application areas. Unfortunately, they often used broad areas, such as 'Finance', 'Production', 'Transportation' and 'Marketing'. They did not usually distinguish between different decision types within manufacturing logistics. Moreover, few investigated if there were differences in OR technique usage between the different application areas.

More generally, relatively few surveys addressed the link between manufacturing logistics problem situations and OR technique usage. Surveys that do contain such evidence have been collected and are shown in chronological order in Table 7-1. All types of surveys have been included, i.e. surveys of organizations, practitioners, application papers etc., as long as they focused on what had actually worked in practice (practice surveys). For each survey, the table specifies:

- The scope in terms of organizational functions and decisions
- The scope in terms of OR techniques
- Problem situation characteristics investigated

Whenever appropriate, results from the reviewed surveys have been used in this thesis. However, the reader should be aware of the following issues limiting the information that could be extracted from them:

- The scope of previous surveys was often restricted to just a few decision types and just one or two of the problem situation characteristics of interest.

- Several surveys only included simulation techniques
- The overview spans 40 years of time. A considerable part of the surveys date many years back. Recent developments in OR and in information technology make their relevance today questionable.
- Due to the lack of established definitions and classifications (see Sections 5.2 and 6.2), different surveys used different lists of OR techniques and application areas, often without defining them in detail. Precise definitions are, however, a prerequisite in order for survey results to be meaningful, and standard classifications are necessary in order to compare and reinforce different surveys' results.
- Mailed questionnaires often suffered from low response rates, and paper surveys often also included OR applications where models only were tested with real-world data, not necessarily providing timely and useful decision support for the involved manufacturing company.

As a consequence, the researcher concluded that previous surveys did not provide a solid enough empirical basis for understanding how OR use depended on problem situation characteristics. Some other researchers made similar conclusions. Fildes and Ranyard (1997), for example, observed that few surveys had examined OR usage in different decision areas and planning horizons. Morgan (1989) noted that only a few researchers had categorized OR use by company size or industry classification. Both examples are over 10 years old. The review summarized in Table 7-1 however, suggests that also more recently, surveys only occasionally investigate how OR applicability depends on problem situation characteristics. This is rather surprising considering the importance of a match between problem situation and OR technique if OR is to be successful (see Section 4.11).

Table 7-1: Surveys investigating how OR technique usage in manufacturing logistics depended on problem situation characteristics

Source	Scope in terms of organizational functions/decisions	Scope in terms of OR techniques	OR usage investigated for ...
Jahangirian et al. (2010)	Manufacturing and business	Simulation	Different decision types Different planning horizons Different industries
Boysen et al. (2008)	Assembly line balancing	Deterministic optimization and queuing theory	Assembly line balancing in Different industries
Stenfors et al. (2007)	Strategic decisions	All techniques	One planning horizon (strategic) Different company sizes
Eom and Kim (2006)	All application areas	All techniques	Different planning horizons
Buxey (2005)	Aggregate production and capacity planning	All techniques	One decision type (aggreg. prod. and cap. planning)
Terzi and Cavalieri (2004)	Supply chains	Simulation	Different decision types Different logistics system scope
Shafer and Smunt (2004)	Operations management	Simulation	Different decision types
Melao and Pidd (2003)	Business process design	Discrete-event simulation	One decision type (business process design)
Smith (2003)	Production plant design and operation	Discrete-event simulation	Different decision types Different planning horizons
Fortuin and Zijlstra (2000)	All application areas	All techniques	Different decision types Different planning horizons
Clark and Scott (1999)	Strategic decisions	All techniques	One planning horizon (strategic)
Ballou and Masters (1999)	Plant location	All techniques	One decision type (plant location)
Eom et al. (1998)	All application areas	All techniques	Different planning horizons
Fildes and Ranyard (1997)	All application areas	All techniques	Different company sizes
Buxey (1995)	Aggregate production and capacity planning	All techniques	One decision type (aggreg. prod. and cap. planning)
Ballou and Masters (1993)	Plant location	All techniques	One decision type (plant location)
Nam and Logendran (1992)	Aggregate production and capacity planning	All techniques	One decision type (aggreg. prod. and cap. planning)
Simulation Study Group (1991)	Manufacturing	Discrete-event simulation	Different decision types
Eom and Lee (1990)	All application areas	All techniques	Different planning horizons

Source	Scope in terms of organizational functions/decisions	Scope in terms of OR techniques	OR usage investigated for ...
Fortuin and Zijlstra (1989)	All application areas	All techniques	Different decision types Different planning horizons
Morgan (1989)	All application areas	All techniques	Different company sizes
Ford et al. (1987)	Production management	All techniques	Different decision types
House (1978)	Distribution	All techniques	Different decision types Different company sizes
Vatter (1967)	All application areas	All techniques	Different company sizes Different industries

Some publications are worth mentioning even though they are not based on OR practice. Olhager and Rapp (1995) examined the link between the various activities in the manufacturing planning and control (MPC) system and OR techniques. They studied 15 textbooks (five on material planning and control, five on production and operations management and five on OR) to find out which OR techniques were used to address the different MPC activities. This study is interesting because it investigates the link between problem situations and OR techniques in important tasks within manufacturing logistics. Its results will, however, not be further discussed here because it is based on what was covered in textbooks, not on what was actually used in practice. Similarly, Wu and Huang (2007) recently investigated OR practice in logistics in Taiwan, thereby also assessing the link between different logistics subfields and OR techniques. Their findings are not further considered in this thesis either, however, because they are based on educator opinion, not empirical evidence.

It should also be noted that several studies investigated the research methods employed in operations management research, such as Pannirselvam et al. (1999). Such studies also investigated the link between the different methods, including quantitative ones, and operations management topics. They are not further considered here because they focus on methods used in *research* rather than for decision support.

The conclusion from the present review is that other researchers' surveys do not provide enough empirical knowledge on how OR technique usage depends on problem situation characteristics. The researcher therefore carried out two surveys himself. As far as possible, the design of these surveys should overcome the weaknesses of previous surveys. It is presented in the next section.

7.3 Survey methodology

The previous section's review concluded that other researchers' surveys have only provided limited knowledge on the link between problem situation and OR technique usage. Based on it, the following requirements for additional surveys are proposed:

- Surveys should specifically examine how OR technique usage depends on problem situation characteristics.

- The scope should include all OR techniques and all manufacturing logistics decisions.
- Precise definitions of all terms and classifications should be used, in particular of OR techniques and manufacturing logistics decision types.
- Only OR applications that successfully supported decision-making in the real-world should be considered.
- The survey sample should be as representative (unbiased) as possible.

These requirements provided the basis for this thesis' surveys. The methodology employed in these surveys is now argued for in detail. First, the reasons are explained why OR applications *described in the literature* have been used as survey objects. The selection of literature sources is then focused on, followed by a detailed account of how papers were selected from these sources.

7.3.1 Why surveying literature?

The objects studied in this thesis' surveys are real-world OR applications documented in the literature. The main reason for this choice is that research literature contains a large number of such application papers. These papers normally provide a detailed description of the particular problem situation studied as well as of the OR technique(s) used. So they contain the information required to examine how OR technique usage depends on problem situation characteristics.

An important advantage of using application papers was that classification could be done rigorously. The lack of commonly agreed-upon definitions and classifications, which can lead to inconsistent answers in for example questionnaires, did not present a problem since the researcher could define rigorous classifications (Chapters 5 and 6) and himself classify all the applications in a consistent manner. An additional important advantage was that unlimited access to application papers at any time facilitated both initial surveying and later reviewing.

These are two key advantages increasing the validity of results compared to questionnaire-based surveys of relevant professionals. The latter often suffers from limited validity because of problems with question wording as well as low response rates (Cooper and Schindler 2003). There is also the danger that the respondents' answers are biased. For example, an expert in discrete-event simulation might exaggerate the applicability of discrete-event simulation. There are also frequently problems with incompletely filled questionnaires. These considerations made the researcher survey papers rather than managers and practitioners.

7.3.2 Selection of literature sources

There are numerous scientific journals and conference proceedings that have published papers describing OR applications. In order to select particularly suitable sources, a preliminary assessment of the following journals/proceedings was carried out:

- *Simulation*
- *Computers and Industrial Engineering*
- *The International Journal of Industrial Engineering*
- *Interfaces*

- *The European Journal of Operational Research*
- *The Journal of the Operational Research Society*
- *Decision Support Systems*
- *Decision Sciences*
- *Operations Research*
- *Manufacturing and Service Operations Management*
- The proceedings of the *Winter Simulation Conference*

The journal *Interfaces* is issued by the Institute of Operations Research and the Management Sciences (INFORMS). It is entirely dedicated to the documentation of practice and implementation of OR, containing numerous papers on real-world applications. These papers normally contain detailed information on the problem situation addressed and the OR technique(s) used. The journal is open for all OR fields and application areas, and it **asks authors to obtain letters from the case companies verifying the actual use and resulting benefits from the OR study**. These characteristics made *Interfaces* particularly suitable for this thesis, in fact, to the researcher's knowledge, *unique*. Other journals in the field of OR are much more concerned with theoretical development of OR models and solution procedures. They sometimes publish application papers, but focus in these papers is normally on novel applications. Inclusion of these journals could have biased the results towards novel applications. Journals in the operations management field also regularly publish 'modelling applications in manufacturing'. Usually, however, the goal of such 'applications' is to better understand a general phenomenon, rather than providing timely and required decision support in real-world companies. While the researcher recognizes the importance also of the former, focus in this thesis is on the latter. The journal *Interfaces* was therefore selected as the main source.

All *Interfaces* issues between 1995 and 2007 were surveyed - a total of over 600 papers. The relevance of earlier issues was considered to be less relevant due to recent, rapid developments in computer science and OR.

Empirical research (Munro and Mingers 2002, Morgan 1989) has shown that discrete-event simulation is a popular technique in practice, probably not much less popular than deterministic optimization. Nevertheless, the survey of *Interfaces* did not reflect this (Table 5-4). Thus, it seems that discrete-event simulation is somewhat underrepresented in *Interfaces*, compared to its frequency of use in practice. In order to increase the validity of findings related to discrete-event simulation, a separate survey of the proceedings of the *Winter Simulation Conference* was carried out as well. The Winter Simulation Conference is an important platform for simulation modelling and contains many application papers, all of them open accessible on the internet. All papers published in the *Winter Simulation Conference* proceedings from 2002-2005 were surveyed. This rather short time frame was chosen because available time was limited, and because little indicated that a more comprehensive study would have provided significant additional insights.

No methodological choice is without limitations. Sources of bias in the selected sample of OR applications are discussed as a part of this thesis' limitations in Subsection 10.4.2.

7.3.3 Criteria for paper selection

The *Interfaces* papers published between 1995 and 2007 were studied one-by-one in order to select those satisfying the following criteria, which follow naturally from this thesis' research objectives and scope:

- The paper reports on successful support of manufacturing logistics decision-making in the real world.
- The company supported was a manufacturing company. NAICS (see Section 3.3) was used to decide if a company could be considered as a manufacturing company.
- Decision support was provided by means of a quantitative model of material/information flows.

90 papers satisfied these selection criteria. The applications described in these papers formed the survey sample. When an application supported several decision types, it counted as several separate applications – regardless whether one single or several different OR techniques were employed. On the other hand, when several OR techniques were used to support decisions of the same type, it counted as one application. This resulted in a sample of 116 OR applications.

In the *Winter Simulation Conference* survey, similar selection criteria were used. In order to be selected, papers had to report on discrete-event simulation applications that supported logistics decision-making in real-world manufacturing companies. They had to provide enough details about the particular problem situation. A number of papers used real-world data to test some methodology, framework or tool. They were not included, unless it was clearly stated that the case company received timely and required decision support. This requirement may unintentionally have led to the exclusion of a few relevant papers. Note that this study is restricted to discrete manufacturing enterprises and their supply chains. Discrete-parts manufacturing is characterized by individual parts that are clearly distinguishable such as circuit boards or engine blocks (Askin and Standridge 1993). Applications in continuous production, such as the petroleum industry, were excluded. Thus, the *Winter Simulation Conference* survey has a slightly narrower scope than the *Interfaces* survey.

51 papers satisfied the selection criteria and were included in the survey sample. If a paper described a discrete-event simulation application that supported several decision types, it counted separately for each type, even if the same basic model was employed. This resulted in a sample of 68 discrete-event simulation applications.

7.4 Survey results and discussion

This section presents the results from the surveys of OR applications described in *Interfaces* and in the proceedings of the *Winter Simulation Conference*. Many of the results are also discussed in this section; the remainder of the discussion is incorporated in Chapter 9.

The scope of the *Interfaces* survey includes all OR techniques; its sample consists of 116 OR applications. The scope of the *Winter Simulation Conference* survey is restricted to discrete-event simulation; its sample consists of 68 discrete-event simulation applications.

The purpose of these surveys is to provide empirical evidence of how the applicability of OR techniques depends on problem situation characteristics (the second specific objective of this

thesis). As explained and motivated in section 7.1, focus is on five problem situation characteristics, namely decision type, planning horizon, logistics system scope, company size and industry.

This section is divided into five subsections, one for each of these characteristics. Each subsection first presents results. They are presented separately for each survey because, as explained above, the scope of the *Interfaces* survey includes all OR techniques, the scope of the *Winter Simulation Conference* survey is restricted to discrete-event simulation. So the samples are taken from two different populations.

The present section also discusses survey results and the applicability of OR techniques for different planning horizons, system scopes, company sizes and industries. As far as the first characteristic is concerned, decision type, survey results and OR applicability will be mainly discussed in Chapter 9.

The discussions in this section focus on the following points:

- An assessment of the reasonableness and generalizability of survey results. In particular, specific sources of bias are outlined, as well as how these sources may have affected the results.
- A comparison with related results obtained by other researchers
- Possible explanations of the results

Whenever natural, implications are also outlined. A summary of key findings and implications will be presented in the next section.

Appendices A and B contain the references to all the papers included in the surveys. In appendix A, references to *Interfaces* papers are classified according to decision type, industry and OR technique(s) used. In appendix B, references to *Winter Simulation Conference* papers are sorted by decision type and year of publication. These appendices constitute a structured collection of 184 OR applications in manufacturing logistics, allowing quick identification of previous cases of interest.

7.4.1 Decision types

Table 7-2 shows for each of the manufacturing logistics decision types defined in Chapter 6 the total number of OR applications published in *Interfaces* between 1995 and 2007, as well as how many times each OR technique was used. Note that in some applications, several techniques were combined. This explains why the numbers indicating technique usage sum up to more than the total number of applications. As the table shows, there have been applications in all decisions types, with a particularly high number in short-term production planning/scheduling and plant location and physical distribution system design.

Table 7-2: The number of OR applications published in *Interfaces* between 1995 and 2007, sorted by decision type and OR technique(s)

<i>Decision type</i>	<i>Number of applications</i>	<i>Techniques used</i>				
		<i>Deterministic optimization</i>	<i>Discrete-event simulation</i>	<i>Queuing theory</i>	<i>Inventory theory</i>	<i>Miscellaneous</i>
Short-term production planning/scheduling	30	25	4	1	1	1
Plant location and distribution system design	21	20	3	1	1	1
Production plant design	16	4	9	7		1
Inventory management	16		3	1	15	
Aggregate production and capacity planning	12	11	2		1	1
Determination of production rules/policies	10	2	5	3	1	2
Transportation management	5	5				
Miscellaneous	6	3	3	1		

Table 7-3 shows for each decision type the number of discrete-event simulation applications published in the *Winter Simulation Conference* proceedings between 2002 and 2005. Most applications concerned production plant design and the determination of production rules/policies.

Table 7-3: The number of discrete-event simulation applications published in *Winter Simulation Conference* proceedings between 2002 and 2005

<i>Decision type</i>	<i>Number of applications</i>
Production plant design	26
Determination of production rules/policies	26
Short-term production planning/scheduling	7
Inventory management	5
Plant location and distribution system design	2
Transportation management	1
Aggregate production and capacity planning	0
Miscellaneous	1

As explained before, few previous surveys distinguished between different decision types within manufacturing logistics. The surveys reviewed by Ford et al. (1987) did and all found that scheduling was one of the most frequently supported application areas. The studies by Fortuin and Zijlstra (2000, 1989) found highest usage in production plant design. Possibly, a closer investigation of the different surveys' samples could help explain this difference, which may, however, also be accidental.

There were also some surveys limited to the practice of simulation. In particular, the survey the *Simulation Study Group* (1991) carried out in the United Kingdom found that most

discrete-event simulation applications in the manufacturing industry were in the areas (using these authors' terms) 'plant layout and utilization', 'analyzing material control rules', 'analyzing required manning levels', 'short-term scheduling and loading', 'capital equipment analysis', and 'line balancing'. 15 year later, the *Winter Simulation Conference* survey results largely confirm these findings. Jahangirian et al. (2010) classified numerous papers describing real-world simulation applications according to application area, technique and industry. Most discrete-event simulation papers within manufacturing logistics concerned (using the authors' terms) 'Manufacturing process engineering' (11), 'scheduling' (6), 'inventory management' (4) and 'supply chain management' (5). This again corresponds well with earlier surveys.

Table 7-2 and Table 7-3 show two important overall points:

- Most OR applications belong to the seven decision types defined in the previous chapter.
- There are clear differences in technique usage by decision type.

The first point has been used for validation in the previous chapter. The second point indicates that 'decision type' is a particularly relevant problem situation characteristic when selecting appropriate OR techniques. In Chapter 9, the applicability of OR techniques will therefore be discussed separately for each of these seven decision types. Here, some observations concerning other decision types are made.

The six applications under 'miscellaneous' concerned:

- Issues related to selecting suppliers (four applications)
- Determining the customer order decoupling point (two applications)

While both the literature and practice indicate that such issues are normally decided based less on advanced mathematical and more on qualitative, holistic considerations, for example strengths-weaknesses-opportunities-threats (SWOT) analysis, the survey indicates that OR in certain situations can offer useful help.

On the other hand, there are certain types of OR models suggested in the literature whereof the survey did not identify any applications, including:

- Business process design (as opposed to the design of physical processes)
- Evaluation of cooperation concepts, such as vendor-managed inventory and collaborate forecasting

These findings deserve some closer attention. Business process improvement is proposed as an application area of discrete-event simulation in books (Banks et al. 1996), in research literature (Nidumolu et al. 1998) and by software companies (www.processmodel.com). However, none of the OR applications surveyed supported administrative process design, neither among those in *Interfaces* nor among those in the *Winter Simulation Conference* proceedings. Also Melao and Pidd's (2003) survey, which explicitly addressed the use of discrete-event simulation in business process design, revealed that discrete-event simulation was seldom used for this purpose.

Business process design may depend too much on human and organizational factors (such as behaviour and performance) to be modelled quantitatively. Melao and Pidd (2003) further discuss this. Such an explanation would also be in agreement with Flood and Jackson's System of System Methodologies (1991), which was introduced in Section 4.15. The System of Systems Methodologies indicates that OR's area of strength is 'simple-unitary' problem contexts. Business process design, however, could reasonably be classified as 'complex' as defined in the System of Systems Methodologies. The System of System Methodologies indicates that other approaches are more suitable than OR to support 'complex' problems such as business process design.

In research literature, OR models have also been used to evaluate various supply chain cooperation concepts. Disney and Towill (2003), for example, assess the effects of vendor-managed inventory. Aviv (2001) evaluates the benefits of collaborate forecasting. Most of these models are based on fictitious supply chains. Their purpose is to increase the general understanding of cooperation concepts. This thesis' surveys did not reveal any cases where OR helped real-world manufacturing companies assess cooperation concepts in their specific context.

This can have several different reasons. It may be because relatively few companies engage in such cooperations. Companies may also fear to lose a competitive advantage if they reveal the benefits obtained from using OR. In this case, OR practitioners should strive to report applications in *Interfaces* and other journals in order to show that OR can support companies in such important strategic assessments. An alternative explanation, however, is that the usefulness of OR is more limited because the benefits of cooperations are difficult to model quantitatively. Such an explanation would again be in agreement with the System of System Methodologies (Flood and Jackson 1991). Cooperations could reasonably be classified as 'complex-pluralist' in the System of Systems Methodologies' sense. Thus, again, the System of System Methodologies indicates that other approaches might be more suitable than OR to evaluate cooperation concepts. See also Subsection 7.4.3, where the paucity of OR applications crossing organizational boundaries is discussed.

7.4.2 Planning horizons

This characteristic was indirectly addressed already as a part of 'decision type'; it is here considered separately since it is a frequently used characteristic in literature discussing OR applicability.

Figure 7-1 shows the planning horizons of the decisions supported by the OR applications surveyed in *Interfaces* (The sum is slightly higher than the total number of OR applications in the sample because certain applications supported several planning horizons).

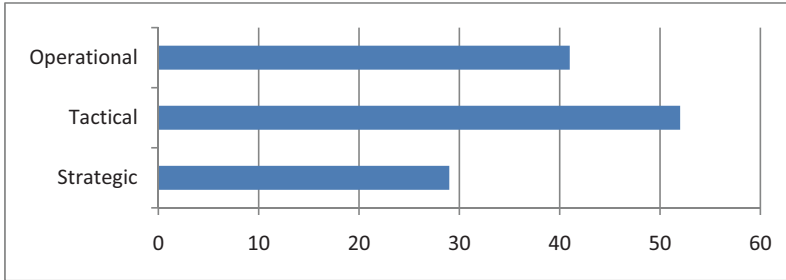


Figure 7-1: The number of strategic, tactical and operational OR applications in manufacturing logistics reported in *Interfaces* between 1995 and 2007.

Figure 7-2 shows the planning horizons of the decisions described in the *Winter Simulation Conference* proceedings.

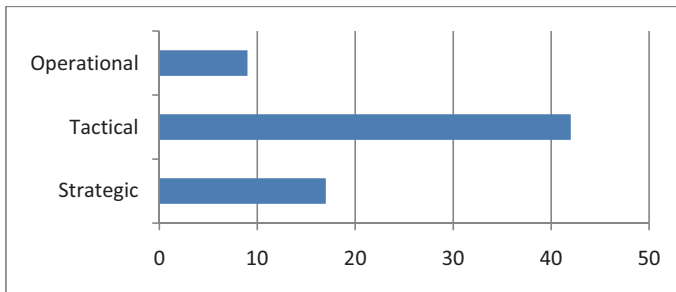


Figure 7-2: The number of strategic, tactical and operational discrete-event simulation applications in manufacturing logistics reported in *Winter Simulation Conference* proceedings between 2002 and 2005.

It is reasonable to assume that the findings from the *Interfaces* survey are somewhat biased towards strategic applications. That is, the proportion of operational applications is likely to be higher in reality than in the sample. The reason is that operational decision support is often standard, implemented in systems, and requiring relatively little company-specific modelling. As a consequence, it is not normally reported in academic literature. On the other hand, the one-of-a-kind decision support provided for strategic decisions, typically very different from case to case, is often worthwhile a research paper.

As far as the *Winter Simulation Conference* survey is concerned, the results seem to be valid. Discrete-event simulation is mainly an analysis and evaluation tool, thus mainly used to support strategic and tactical decisions. Still, the fact that nine of the applications were operational shows that discrete-event simulation has a potential to be applied in operational planning and control as well (typically to evaluate production plans/schedules developed by other techniques).

A number of previous surveys studied planning horizons. Smith (2003) surveyed papers on discrete-event simulation applications in manufacturing and categorized them into ‘manufacturing system design’ and ‘manufacturing system operations’. He found that the number of papers addressing ‘manufacturing system design’ was somewhat higher than the number of papers addressing ‘manufacturing system operations’. His results cannot be

compared directly to the *Winter Simulation Conference* survey because he used a different categorization of planning horizons. Nevertheless, the two surveys agree that discrete-event simulation is somewhat more frequently used for design than for operation, but that it has had applications at both levels. Jahangirian's study (2010) also found that discrete-event simulation had been used at the operational level.

Eom and Kim (2006), Eom et al. (1998) and Eom and Lee (1990), investigating decision support system applications over several decades, found OR techniques to be an essential element in decision support systems and between 20% and 30% of all applications to be strategic. This is similar to the present findings. Fortuin and Zijlstra (2000) surveyed 160 OR projects carried out by a consultancy bureau and also found a distribution of planning horizons that is very similar to the one in the *Interfaces* survey. Stenfors et al. (2007), investigating decision support tool usage in Finland, conclude that OR plays an active role in the market for strategic-level tools. Clark and Scott (1999), finally, found that OR practitioners *are* involved with strategic tasks, and that they use (mainly quantitative) tools to support these tasks.

Thus, there is a considerable number of surveys suggesting that OR has supported all planning horizons. This is somewhat in disagreement with the claims made by Ackoff (1987), Rosenhead and Mingers (2001a) and others, restricting the applicability of OR to operational and tactical issues. There is much evidence that at least certain strategic decisions have benefitted from OR as well. A closer look at the strategic decisions supported in the *Interfaces* and *Winter Simulation Conference* surveys reveals that they concerned mainly **plant location**, **plant capacities** and **equipment capacities**.

Doubtlessly, qualitative factors weigh heavily in such issues. Plant location in a foreign country, for example, requires evaluation of human capital, infrastructure, industrial environment, political factors etc. Still, OR seems to play a certain role, typically as one element in a more comprehensive evaluation of different options. As explained in Section 4.13, OR's strength is that it provides an objective and rational analysis with quantitative answers. As exemplified by the *Felleskjøpet* case study presented in the next chapter, these features can contribute to the fact that OR is used in strategic decision-making. In conclusion, OR appears to be useful not only for operational/tactical decisions, but also for certain well-defined strategic questions.

7.4.3 Logistics system scopes

Figure 7-3 shows the logistics system scopes the models described in the *Interfaces* papers had. These scopes were defined in Subsection 3.2.3. As the figure shows, only four applications crossed organizational boundaries. They are described by Cholette (2007), Shirodkar and Kempf (2006), Yoshizaki (1996), and Lee and Billington (1995).

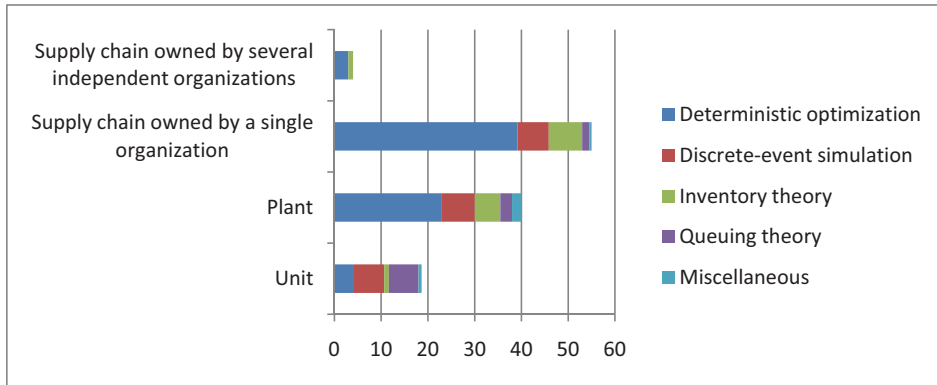


Figure 7-3: Scopes of the logistics systems modelled by OR (Number of applications per scope and OR technique in *Interfaces* survey)

Figure 7-4 shows the system scopes of the discrete-event simulation models presented at *Winter Simulation Conferences* between 2002 and 2005. Just three applications concerned supply chains owned by single organizations, and just two applications crossed organizational boundaries. The number of applications with these two scopes is even misleadingly high. In fact, there were only two papers reporting on discrete-event simulation models of supply chains (Jain and Leong 2005, Dalal et al. 2003). These models counted as several applications because they supported decisions of several types (see Subsection 7.3.3 for details about how applications were counted).

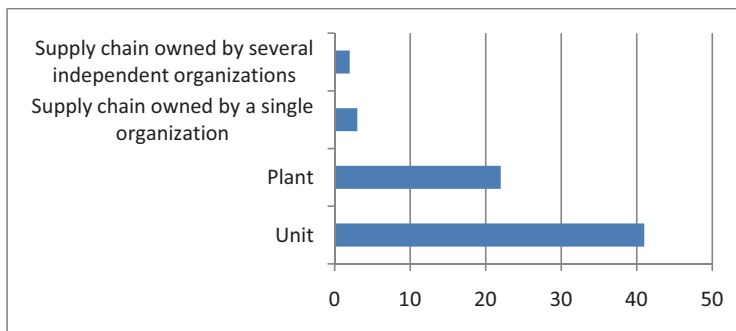


Figure 7-4: Scopes of the logistics systems modelled by discrete-event simulation (Number of applications per scope in *Winter Simulation Conference* survey)

The results from the *Interfaces* survey are likely to be somewhat biased towards applications with supply chain scopes. This is because applications at unit/plant levels are often standard and therefore not published (such as the use of basic single-stage inventory models). The relative number of applications at unit/plant level is therefore probably higher in reality than in the *Interfaces* survey sample.

Neely's (1993) study is worth mentioning, even though it was not restricted to decision support in practice. He examined the scope of research published in the *International Journal of Operations & Production Management*. He found that research focusing on large systems

(macro orientation) was mainly concerned with discussing organization and human issues (soft research emphasis); research focusing on a very specific aspect such as scheduling a single machine (micro orientation) was primarily mathematical (hard research emphasis). Figure 7-5 illustrates this. It is somewhat in disagreement with the *Interfaces* survey, which revealed a considerable number of OR applications in supply chains. As long as the supply chain considered is part of the same organization, OR applications do not seem to be uncommon.

		Orientation	
		Micro	Macro
Emphasis	Soft		■
	Hard	■	

Figure 7-5: Research scopes identified by Neely (1993)

The following survey findings are now discussed in more detail:

- The low number of papers on OR applications that cross organizational boundaries (both surveys)
- The high number of deterministic optimization applications at the supply chain level (*Interfaces* survey)
- The low number of discrete-event simulation applications at this level in the *Winter Simulation* survey

Low number of papers on OR applications that cross organizational boundaries

This finding is consistent with Terzi and Cavalieri (2004), who found that most applications of discrete-event simulation concerned a single organization. It was to be expected in the light of the difficulty companies still today experience to make inter-organizational collaboration work (Busi 2005). Collaborative logistics design and planning seems to be in its infancy and only performed by the most mature companies. Challenges such as differing strategies and interests, lack of trust and openness, limited willingness to share data and lacking IT-integration (Hieber 2002) still seem to present major obstacles to successful collaboration.

It is thus not surprising that Neely (1993) found that most research at this level concentrated on soft issues. Only when such issues are settled, quantitative models can be applied. This is emphasized by research on the limitations and applicability of OR, reviewed in Section 4.15, stressing that high consensus between stakeholder is imperative if OR is to work (Rosenhead and Mingers 2001a, Jackson and Keys 1984, Hopwood 1980). In terms of the System of System Methodologies (Flood and Jackson 1991), independent supply chain actors are usually *pluralist* or even *coercive*. According to Flood and Jackson (1991), they need to be unitary, however, in order for OR to be applicable. This provides an explanation for limited opportunities to apply OR in inter-organizational logistics design and planning.

Nevertheless, recent years have witnessed plenty of research aiming to mitigate the organizational obstacles to collaborations, for example by means of adequate contracts and incentive mechanisms. IT integration across the supply chain is also relentlessly improving. An increase in OR applications crossing organizational boundaries is therefore to be expected in the future.

High number of deterministic optimization applications at the supply chain level

Figure 7-3 shows that *Interfaces* published a high number of papers describing successful OR applications at the single-organization supply chain level. A closer look at these papers revealed that deterministic optimization has supported supply chain management at all planning horizons, namely:

- Plant location and distribution system design (strategic)
- Aggregate production and capacity planning (tactical)
- Short-term production planning/scheduling (operational)

This type of OR application has allowed companies to achieve centralized, coordinated logistics decision-making across a network of plants and warehouses. The present study thus indicates that for this purpose, deterministic optimization has a rather high application potential.

Low number of discrete-event simulation applications at the supply chain level

While discrete-event simulation has had numerous successful applications at the unit and plant levels, the *Winter Simulation* survey revealed very few applications in supply chains. The *Interfaces* survey shows that such applications have taken place, but, at least compared to optimization, they seem to be less frequent.

Also some other researchers made similar observations. Chwif et al. (2002), comparing the use of spreadsheets to simulation in supply chains, note that ‘static and deterministic methods still rule’. Shafer and Smunt (2004) found few simulation applications in supply chain management. And even after several years with focus on supply chain management in business and research, Jahangirian et al.’s (2010) survey only found five discrete-event simulation applications in supply chain management, compared to a much higher number at the unit/plant level.

Such findings are somewhat surprising given numerous papers emphasizing the usefulness of discrete-event simulation in the supply chain context (Kleijnen 2005, Terzi and Cavalieri 2004, and Banks et al. 2002). There are also papers that describe frameworks, experiments and software prototypes dealing with supply chain simulations (for example Liu et al. 2004). Moreover, there are several commercially available discrete-event simulation systems specifically developed for supply chain simulations, e.g. e-SCOR by Gensym or Supply Chain Guru by LlamaSoft.

How can this apparent paucity of discrete-event simulation applications in supply chain management be explained? One likely reason is that discrete-event simulation modelling, which has a long tradition in the analysis of production systems within four walls, needs time to adapt to the more recent, wider perspective of supply chain management. Theoretical frameworks and conceptual models must be developed, practitioners trained and

methodologies reviewed. It also seems that existing discrete-event simulation software needs some adjustment in order to be fully appropriate to the new situation. Van Der Zee and Van Der Vorst (2005), for example, observe that control-related issues - despite their key importance - often remain hidden in such software and are therefore not easily communicated with decision-makers.

Interviews with relevant experts also indicate that developing and maintaining valid models of real-world supply chains tends to be rather challenging. Numerous reasons have been stated, including:

- It is very time-consuming to get a detailed enough understanding of supply chain processes to allow quantitative modelling. Usually, the interrelationships in supply chains are very complex. Moreover, once this understanding is acquired in one particular situation or industry, it cannot be easily transferred to other situations/industries.
- Supply chain activities usually involve many human and behavioural elements that are difficult to capture quantitatively.
- Supply chains structures and processes change rapidly, which makes model maintenance a challenging, time-consuming endeavour.
- Much data is required and data gathering is difficult (Kaczmarek and Stüllenbergh 2002).
- Knowledge and experience in discrete-event simulation of supply chains is highly recommended, but not easily available.
- Human errors in modelling and data collection/analysis are very likely given the size and complexity of supply chain models.

These challenges suggest that discrete-event simulation is more difficult to apply in supply chains than within a single plant. They can imply that supply chain simulations will never enjoy the same success as unit/plant simulations.

Note that the above points illustrate challenges related to supply chain modelling in general, not only discrete-event simulation. Nevertheless, deterministic optimization has had many successful applications. The researcher suggests the following explanations, which must be subject to more detailed investigations:

- Deterministic optimization models allow the use of aggregated values. In discrete-event simulation models, however, data aggregation opportunities are more limited.
- Deterministic optimization models of supply chains typically allocate tasks to scarce resources. Discrete-event simulation models tend to model the supply chain as processes, i.e. resources where materials/information are processed, move between the resources, and form queues in front of them. At the supply chain level, the former view may be more useful and more easily expressed by a quantitative model. The latter view might be most appropriate for material flows *within* a production plant.
- One may even be argued that the deterministic optimization models used in supply chain management are of somewhat limited validity. Still, they are used because they

can automatically and periodically calculate plans, and they can financially justify improvement initiatives. These are attractive features not provided as easily by discrete-event simulation.

More research is needed to understand the situations in which discrete-event simulations can be usefully applied at the supply chain level. In the meantime, managers and practitioners should be aware that this type of endeavour can be challenging and time/resource-consuming. If software vendors indeed have limited success with their supply chain simulation tools, as indicated by Semini et al. (2006), the present research can offer some explanations.

7.4.4 Company size

In almost all *Interfaces* papers, it was possible to find information about the size (number of employees) of the case companies. Most of them had over 500 employees. Also in the *Winter Simulation Conference* proceedings, the majority of case companies were large.

Other researchers examining the issue made similar findings. Fildes and Ranyard (1997), reviewing a number of relevant surveys, summarized that ‘the larger the size of the parent organization, the more likely they were to possess an OR group’. Morgan (1989) concluded that survey studies provided evidence that size and extent of OR use are positively correlated. Also more recently, Stenfors et al. (2007) found that larger companies clearly use OR techniques more often than smaller companies. Thus, over the years, considerable empirical evidence has been collected that OR is most frequently applied in large companies.

The researcher proposes the following explanations:

- Only when companies have eliminated gross inefficiencies they recourse to OR models for further improvement. Large companies are more likely than small companies to have reached this level of maturity (due to a larger number of specialized personnel, for example).
- The larger the cost base to which OR models are applied, the more likely savings outweigh model development costs.
- Large companies have more resources than small companies for analysis and improvement initiatives (such as OR applications). The chances that resources are allocated to OR are therefore higher in large companies than in small companies, where only the very most promising initiatives get a chance.
- It can be argued that quantitative models of large companies are likely to be more accurate (law of large numbers), thus more useful. For example, averages are more appropriate when dealing with large numbers (Murphy 2005b).

These findings have several implications. Firstly, large companies should assess the opportunities in OR, if they have not done so yet. OR can probably provide them with a competitive advantage. The present thesis can help them identify potential application areas.

Secondly, company size appears to be a useful first criterion to assess the applicability of OR in manufacturing logistics: As a rule of thumb, it can be posited that the larger the company, the greater the chance that they can benefit from OR. That said, it must also be stressed that simple models, such as basic inventory-theoretic formulae, can of course be beneficially applied also in small companies.

Finally, Stenfors et al. (2007) remark that economies are becoming unified and companies larger. As a consequence, they predict increasing use of OR in the future.

7.4.5 Industries

Table 7-4 shows in which industries the OR applications published in *Interfaces* were carried out. It also shows how many times each OR technique was used in each industry.

Most applications have been reported in the computer and electronic product industry. Among them, the majority concerned computers, computer-related equipment and semiconductors. Three other industries have also had frequent publications of applications, namely the food industry, the chemical industry and the transportation equipment industry (including the automotive industry). These four industries stand for over 70% of all the OR applications surveyed.

Table 7-4: Number of OR applications per industry (*Interfaces* survey)

<i>Industry</i>	<i>Number of applications</i>	<i>Techniques used</i>				
		<i>Deterministic optimization</i>	<i>Discrete-event simulation</i>	<i>Queuing theory</i>	<i>Inventory theory</i>	<i>Miscellaneous</i>
Computer and electronic product manufacturing	34	15	10	4	9	4
Food manufacturing	17	16	2	1		
Chemical manufacturing	17	12	6		3	
Transportation equipment manufacturing	16	5	6	9	2	2
Primary metal manufacturing	6	6				
Printing and related support activities	5	2	1		2	
Machinery manufacturing	4	1	1		2	
Wood product manufacturing	3		3			
Paper manufacturing	2	2				
Plastics and rubber products manufacturing	2	2				
Electr. equipment, appliance, and component manuf.	2	1			1	
Beverage and tobacco product manufacturing	2	2				
Apparel manufacturing	2	2				
Petroleum and coal products manufacturing	1	1				
Fabricated metal product manufacturing	1	1				
No information available	2	2				

As far as the *Winter Simulation Conference* survey is concerned, the number of applications per industry is shown in Table 7-5. The majority of applications again belong to the computer and electronic product industry, closely followed by the transportation equipment industry (mainly automotive). These two industries account for over 50% of all the applications in the survey.

Table 7-5: Number of applications per industry (Winter Simulation Conference survey)

<i>Industry</i>	<i>Number of applications</i>
Computer and electronic product manufacturing	21
Transportation equipment manufacturing	17
Chemical manufacturing	7
Fabricated metal product manufacturing	6
Primary metal manufacturing	4
Printing and related support activities	2
Wood product manufacturing	2
Machinery manufacturing	1
Electrical equipment, appliance, and component manuf.	1
Apparel manufacturing	1
Nonmetallic mineral product manufacturing	1
Miscellaneous manufacturing	1
No information available	4

Few researchers have explicitly investigated OR use by industry. Jahangirian et al. (2010) classify a large number of simulation application papers according to application area, simulation technique and industry (as done in this thesis) and observe that discrete-event simulation has been applied in a variety of industries. Vatter (1967) investigated the link between industry and OR use in general. However, this survey is over 40 years old. Moreover, the classification used there is highly aggregated, grouping all manufacturing industries into four groups. Between these four groups, the survey revealed no clear evidence on differences in OR application.

It must be remembered that only manufacturing logistics decisions have been considered in the surveys. In particular, blending problems, i.e. situations in which inputs must be blended in some desired proportion to produce goods for sale (Winston 2004) are outside scope as they are considered as product design. It is reasonable to assume that the petroleum, the chemical and the food industries otherwise would have had some blending applications.

The leading position of the computer and electronic product industry is probably due to its high technological level. There is awareness of and trust in advanced technological solutions such as OR-based planning techniques. Besides, this industry benefits from publishing successful use of computer-based tools. In the chemical and the transportation equipment industries, production technology is also sophisticated, which again facilitates adoption of advanced planning solutions.

In the food industry, a closer look at Table 7-4 reveals that the technique most frequently used was deterministic optimization. On the other hand, both Table 7-4 and Table 7-5 show that few papers described discrete-event simulation applications. This finding suggests frequent use of deterministic optimization, but limited use of discrete-event simulation in the food industry.

A possible explanation is as follows. In the food industry, technological know-how is mainly found at centralized, higher hierarchical levels. Frequent use of deterministic optimization reflects a need to centrally plan and coordinate activities across units and plants. Discrete-

event simulation is mainly used to model production processes. These processes, however, tend to be relatively simple and run by low-educated operators. Such an environment may be less favourable to advanced modelling.

Finally, note that almost half of all the applications of inventory theory were reported in the computer and electronic product industry. Computers and electronic components have a high unit price, which implies high inventory carrying costs. In addition, the life-cycles of electronic products are typically very short, which leads to a high risk of obsolescence. Both these characteristics increase the importance of correct sizing of inventory levels. It probably explains why inventory models seem to enjoy particularly high usage in this industry.

7.5 Summary

This chapter has presented and discussed the results from two surveys of OR applications described in literature. There are hundreds of such OR applications that have successfully supported manufacturing logistics decision-making, indicating that OR has a considerable potential in the field.

The purpose of both surveys was to examine how the use of OR techniques depended on the following five *problem situation characteristics*: Decision type, planning horizon, logistics system scope, company size and industry. The first survey studied OR applications published in *Interfaces* between 1995 and 2007, the second discrete-event simulation applications published in the *Winter Simulation Conference* proceedings between 2002 and 2005. These sources were selected because they focus on successful OR applications. Together, the surveys provided a sample of 184 applications, which was used to gain a better understanding of the problem situations in which OR techniques have been successful.

The survey findings suggest that among the five characteristics investigated, decision type and company size are most useful for a first assessment of the different OR techniques' applicability. As far as **company size** concerns, most applications have been carried out in large companies. This indicates that the larger the company, the more likely it can benefit from OR. Large companies should therefore assess the opportunities of OR, if they have not done so yet. The guidelines in Chapter 9 provide a good means for them to identify potential application areas. Smaller companies can certainly also take advantage of OR models, but it may be wise for them to stick to small, simple models.

As far as **decision types** are concerned, the surveys indicated that most OR applications belong to the seven decision types defined in Chapter 6. As opposed to Morgan's (1989) study, they also revealed an unequal distribution of OR technique usage for the different decision types. This suggests that the applicability of each OR technique is affected by the decision type considered. Given a real-world problem situation, the decision type thus provides an indicator as to which OR techniques are likely to be suitable. This is why the framework introduced at the end of Chapter 6 (Figure 6-2) provides a good overall structure of the guidelines on OR applicability (Chapter 9). The guidelines elaborate on OR technique applicability separately for each decision type, based on survey findings and existing knowledge.

As far as **planning horizons** is concerned, the applications surveyed addressed decisions at all planning levels, i.e., strategic, tactical, and operational. Strategic decisions often concerned plant locations, plant capacities, and equipment capacities. Combining these findings with previous surveys' findings, which are similar, one can make the following implications:

- OR seems to be most frequently used to support operational/tactical decisions, but it has had numerous strategic applications as well. Claims stating that OR is not suitable for strategic, one-of-a-kind decisions should therefore be stated more carefully: Strategic decisions cannot be made based on OR models alone; however, OR models can for certain strategic decisions constitute a useful element in a more comprehensive evaluation of the available options.
- While discrete-event simulation is mainly a tactical analysis and evaluation tool, it has a potential to be applied in operational planning and control as well (typically to evaluate production plans/schedules developed by other techniques).
- Simply looking at the planning horizon does not help determine if a decision can benefit from OR. In other words, planning horizon by itself is not a good criterion to determine OR technique appropriateness.

Regarding the **scope of the logistics systems** modelled, several important findings were made. Few papers described the use of OR techniques at the inter-organizational level. This finding reflects the notorious difficulties to settle organizational issues between companies, such as alignment of strategies and interests, trust and openness, information sharing etc., which is however required before quantitative OR can be applied. The advocates of 'soft OR' offer a range of approaches that they claim are more suitable to address the typical soft issues inhibiting inter-organizational collaboration (Rosenhead and Mingers 2001b). As companies become more and more aware of the benefits of collaboration, there should be plenty of opportunities to apply such approaches in practice.

The second important finding is that deterministic optimization has helped many multi-plant companies achieve centralized, coordinated decision-making at the strategic, tactical as well as operational decision level. So for companies desiring such centralized control, deterministic optimization is likely to be useful. On the other hand, somewhat more limited usage of discrete-event simulation at the supply chain level has been identified. It seems that the complexity of most supply chains, combined with the detailed modelling level usually required by discrete-event simulation, often make this type of OR application difficult and time/resource-consuming. While more research is required to understand the situations in which discrete-event simulation can be useful for supply chain analysis, managers, practitioners and software developers must be aware of the challenges related to such endeavours.

Most OR applications were reported in four **industries**, namely computer and electronic product manufacturing, food manufacturing, chemical manufacturing and transportation equipment manufacturing (especially the automotive industry). There were also some differences in technique usage. Most importantly, there were numerous applications of deterministic optimization in the food industry, but hardly any discrete-event simulations. It is also interesting to notice that almost half of all the applications of inventory theory were in the computer and electronic product industry. Some of the differences in OR use by industry are likely to be due to differences in product and process characteristics. Nevertheless, many of them do not seem to be due to unequal degrees of OR technique applicability, but to different levels of technological awareness and education. This indicates numerous unexploited opportunities for OR-based improvements in technologically less advanced industries.

The present chapter has provided empirical evidence of how OR usage depended on five specific problem situation characteristics. However, numerous other characteristics can be relevant to determine if a particular OR technique is suitable for a given problem situation. The remainder of this thesis therefore extends the scope to other relevant characteristics. In the next chapter, a number of case studies will be presented. They helped identify such characteristics.

8 Case studies

It is important to realize that the descriptions of OR applications in *Interfaces* and the *Winter Simulation Conference* proceedings, surveyed in the previous chapter, are very detailed and not limited to the five problem situation characteristics studied there. So even though the previous chapter's research strategy was called survey, it actually provided the researcher with a much deeper contextual understanding than would have been possible with the typical, questionnaire-based survey. In particular, it provided him with numerous details on the situations in which OR techniques were used, as well as on *how* the various OR techniques are used to support decision-making. This knowledge provided key input for achieving this thesis' third objective, the development of the guidelines.

Nevertheless, what can be learned from written descriptions will always be limited compared to own field-based observations and participation in real-world settings. In order to strengthen the knowledge base for the guidelines, the researcher therefore performed a number of case studies. The purpose of these case studies can be stated by means of two questions:

- Why was a certain OR technique chosen?
- How was the technique used to support decision-making?

The first question refers to the problem situation characteristics that led to a certain technique choice; the second question directly comes from this thesis' third objective, explaining how OR works. The two questions cover the main types of information needed for the guidelines.

The remainder of this chapter is organized as follows. First, methodological issues are covered. The choice of case studies as a research strategy is argued for, as well as the selection of cases. The data collection methods are then presented, followed by the way case evidence was analyzed. Sections 8.2 through 8.4 contain descriptions of each case, with focus on the problem situation characteristics and on how OR was used for decision support. A preliminary analysis is also included in this chapter, where the three cases are characterized along the five problem situation characteristics identified in the previous chapter.

8.1 Methodology

A *case* is a spatially delimited phenomenon observed at a single point in time or over some period of time; a *case study* may be understood as the intensive study of a single case where the purpose of that study is – at least in part – to shed light on a larger class of cases (Gerring 2007). McCutcheon and Meredith (1993) stress that ‘...embracing a field investigation technique such as case studies is bound to make the individual researcher, and the field [operations management] in general richer and better prepared to solve real operations management problems’.

The specific advantage of case studies, compared to a study of OR applications described in the literature, is that even greater depth can be achieved by means of direct contact with key informants. Case study research places emphasis on the full context of a few events or conditions and their interrelations (Cooper and Schindler 2003). According to Yin (2003), the main characteristic of the case study research strategy is that it examines a contemporary phenomenon in its real-life context, especially when the boundaries between phenomenon and context are not clearly evident. Both Yin (2003) and Voss (2009) point out that case research allows questions of ‘why’ and ‘how’ to be addressed with a relatively full understanding of the nature and complexity of the complete phenomenon. This suggests that case studies are an

appropriate research strategy to address the above two questions. The knowledge and experience obtained will allow the development of practically relevant guidelines in the next chapter.

Case studies can be used for exploration, theory building, theory testing and theory extension/refinement (Voss 2009). Exploration is about uncovering areas for research and theory development; theory building identifies/describes key variables and linkages between them; theory testing tests the theories developed in the previous stages; theory extension/refinement aims to better structure the theories in light of the observed results (Voss 2009, Handfield and Melnyk 1998). In these terms, the present case studies are best characterized as theory building because their main purpose was to identify key variables related to the application of OR techniques, such as problem situation characteristics that make OR a good choice. The theory to which the present thesis makes a contribution can be called the theory of the practice of OR, as suggested and introduced by Murphy (2005a, 2005b, 2005c).

8.1.1 Selection of cases

A frequently discussed question in methodological literature is how many cases to carry out (Voss 2009, Eisenhardt 1989). The advantage of a single case is that greater depth is achieved, the disadvantage limited generalizability. The higher the number of cases, the better external validity can be achieved, but it comes at the price of depth and increasing resource requirement (Voss 2009).

A related, important question is how to select cases. If the purpose is to understand some general phenomenon, such as OR applications, the cases should be chosen such as to provide insights into the population of instances of this phenomenon. As Stake (2000) explains, cases are chosen because it is believed that understanding them will lead to better understanding, perhaps better theorizing, about a still larger collection of cases. Since the number of case studies by definition is always relatively small, random sampling is problematic, and case selection must normally be based on purposive, non-random procedures (Gerring 2007). Gerring (2007) presents nine techniques to do so, whereof the first is the *typical-case approach*. In this approach, one or several cases are selected that are typical instances of the phenomenon to be studied. The second approach is the *diverse-case*, where two or more cases are selected such that maximum variety is achieved among relevant variables. Stake emphasizes that cases should be chosen that seem to offer opportunity to learn. 'That may mean taking the one most accessible or the one we can spend the most time with. Potential for learning is a different and sometimes superior criterion to representativeness' (Stake 2000). Eisenhardt (1989) and Yin (2003) point out that cases are often selected according to a set of criteria. Robert and Helen Lynd (1929), for example, defined six criteria to select a city as representative as possible of contemporary American life.

In the present doctorate study, cases were selected according to such a set of criteria. Specifically, the researcher looked for OR applications that satisfied the following requirements:

- They used one or several of the OR techniques typically used to support manufacturing logistics (deterministic optimization, discrete-event simulation, queuing theory, inventory theory).

- They supported one or several of the manufacturing logistics decision types most frequently supported by OR (See Chapter 6).
- Different cases used different OR techniques and supported different decision types.
- They were carried out by SINTEF or in a setting where SINTEF played an important, active role, providing the researcher access to relevant informants and documentation.

This set shows that the selection approach chosen was a combination of the typical-case and the diverse-case approach. The first two criteria assured typical cases, the third diverse cases. The fourth criterion is in line with Stake's (2000) requirement to accessibility.

The number of cases was also driven by these criteria. That is, the number of cases that satisfied these criteria was relatively small. The second factor affecting the number of cases was time. In order to stay within the resources made available for this doctorate study, the candidate had to choose a number of case studies that provided maximum knowledge with minimum resource requirement.

These considerations led to the selection of three cases, which will now be justified.

Case 1: Felleskjøpet Trondheim

In the first case, Felleskjøpet Trondheim used mixed-integer linear programming to determine which feed variants to produce at which plants, and which farmers to supply from which plants. This OR application thus used a deterministic optimization model and supported decisions related to plant location and distribution system design, so the first two selection criteria were satisfied. The third criterion must be seen in relation to the other cases. Felleskjøpet Trondheim subcontracted the modelling analysis to SINTEF Technology and Society, who used operations researchers as well as economists in the task. Access to relevant information was further simplified by the fact that the former logistics manager at Felleskjøpet Trondheim by the time of this study worked at SINTEF Technology and Society. The first criterion was thus also satisfied.

Case 2: Gilde Norsk Kjøtt

The second case involved the development and use of a discrete-event simulation model at the Norwegian meat corporation, by the time called Gilde Norsk Kjøtt. The company used the model to analyze various capacity- and control-related issues during the extension of its plant at Steinkjer in central Norway. Such decisions fall into the decision types 'production plant design' and 'determination of production rules/policies', so criteria one and two were met. The simulation expert at SINTEF Technology and Society carried out the modelling and analysis and summarized the work in a report. He thereby provided the researcher with both oral and written information, which fulfilled requirement number four.

Case 3: Mustad

In the third case, the Norwegian manufacturer of fish hooks, Mustad, pilot tested a state-of-the-art multi-echelon inventory management system with the purpose to reduce safety stock levels in its global network of plants and warehouses. Even though in this case, OR was only pilot tested, the first two requirements can be considered as met (inventory theory for inventory management) because the case provided a deeper understanding of the situations amenable to multi-echelon inventory theory. Relevant material was readily accessible since

the pilot test was performed in collaboration with SINTEF as a part of the research project ORIGO, and the researcher himself played a central role in assessing and testing the OR technique.

Note also that the cases covered three of the five most frequently reported types of OR applications in *Interfaces* (see Table 7-2). The three cases thus fully satisfied criterion one, two and four. They also satisfied criterion number three. This can be best seen by placing the cases into the decision-technique matrix introduced at the end of Chapter 6 (Figure 8-1). In fact, the three cases covered three of four relevant OR techniques and four of seven relevant decision types. Thus, despite a limited number of cases, wide variety among OR applications in manufacturing logistics was achieved.

		OR technique			
		Deterministic optimization	Discrete-event simulation	Queuing theory	Inventory theory
Decision type	Short-term production planning/scheduling				
	Plant location and distribution system design	○			
	Production plant design		○		
	Inventory management				○
	Aggregate production and capacity planning				
	Determination of production rules/policies		○		
	Transportation management				

Figure 8-1: The three cases selected cover three of four OR techniques and four of seven decision types.

As an additional test of the quality of the case sample selected, the six tests by Miles and Huberman (1994, p. 34) can be applied. This leads to the following answers:

1. Is it relevant to the conceptual frame and research questions? *Yes, since the cases increase the understanding of the applicability of OR to support manufacturing logistics.*
2. Will/can the phenomena to be studied appear? *Yes, each case concerned an OR application.*
3. Is it one that enhances generalizability? *In this thesis, case studies are used in combination with surveys. Generalizations are not made solely based on the three case studies, the entire survey sample of almost 200 OR applications has been used to make some indications on the applicability of OR techniques.*
4. Can believable descriptions/explanations be produced? *Yes, as the case descriptions in the subsequent sections showed.*
5. Is it feasible, in terms of time, money, access to people, personal work style? *The time frame was limited, which is why the number of cases was kept low, and case*

descriptions were limited to information that was strictly necessary. Key informants were accessible as they are colleagues of the researcher.

6. Is it ethical in terms of informed consent, potential benefits and risks and relationships with informants? *In each case, the researcher checked with key informants that the case descriptions did not contain any confidential information.*

Miles and Huberman's (1994) tests are therefore considered as satisfied and the selection of cases deemed appropriate.

For the sake of precision, the following should be noted about the selected cases. Stake (2000) distinguished between three types of case studies: In the *intrinsic* case study, the researcher first and last wants better understanding of this particular case. In an *instrumental* case study, a particular case is examined mainly to provide insight into an issue or to redraw generalization. Finally, if several instrumental case studies are carried out, he called it a *collective* case study.

At a superficial level, the present study constitutes a collective case study because it consists of several instrumental cases. This is correct if the phenomenon scrutinized is defined as 'OR applications in manufacturing logistics'. However, it can be seen from the description of OR techniques in Chapter 4 that different techniques work in quite different ways. The reasons why a particular technique is chosen typically differ, as well as the way they support decision-making. So if 'why' and 'how' are to be investigated, different techniques' applications are best considered as different phenomena. In particular, the three cases selected should then be considered as instances of three different phenomena. Consequently, it is more correct to talk about three single instrumental case studies. This reduces generalizability of the findings; on the other hand, it allowed the study of a much greater variety, which was necessary because the overall objective of this thesis was to provide an *overview* of OR applicability in manufacturing logistics.

8.1.2 Data collection

As explained above, SINTEF played a central role in all the three cases studied. This made data collection convenient. The following data collection methods were used:

- *Documentation*: In all the cases, the researcher had access to various types of secondary literature, including SINTEF reports, slide shows and web pages.
- *Interviews with key informants*: The researcher discussed the cases directly with SINTEF personnel who played a key role in the OR applications considered. This way, information not available in written form could be collected. It also helped clarify some unclear points.
- *Participation*: In the Mustad case, the researcher played a central role himself in assessing and testing the OR technique. This gave him access to relevant information at a level of detail which would otherwise have been difficult to reach. From a data collection perspective at least, the Mustad case thus in fact contained elements of action research as a research strategy.

Based on these sources, descriptions of each case were developed. Only information strictly necessary for achieving the purpose of the case studies was included:

- The problem situation
 - General information about the case company
 - Key characteristics of the logistics system considered
 - The decisions to be supported
- The use of OR for decision support
 - Why an OR techniques was selected
 - How the technique was used for decision support

8.1.3 Data analysis

In data analysis, the collected quantitative and qualitative evidence is examined, categorized, tabulated, tested or otherwise recombined to address the research question or objective (Yin 2003). Yin (2003) distinguished between three general strategies: *relying on theoretical propositions*, where initial hypotheses or propositions are assessed by means of the new evidence; *thinking about rival explanations*, where evidence is compared to several competing hypothesis; and *developing a case description*, aiming at a descriptive framework for organizing the case study. Yin further proposes five specific analytic techniques that can be used with any of these general strategies: pattern matching, explanation building, time-series analysis, logic models and cross-case synthesis. Essentially, *pattern matching* and *explanation building* compare a predicted pattern of some variables to the actual pattern in the case. For more exploratory case studies, where predicted patterns may not exist, Strauss and Corbin's *grounded theory* (1998) provides a structured approach to generating such patterns.

Voss (2009) also explains how case studies are used to shape hypotheses, and how they are used to test them. Moreover, he presents a number of specific ways of analyzing case data. In the *case dynamics matrix*, a set of forces for change is displayed and consequential processes and outcomes are traced. A second form is to use case data to *test various predictions*. A *causal network*, finally, is a 'display of the most important independent and dependent variables [...] and of the relationships among them' (Miles and Huberman 1994).

In the present thesis, case evidence was analysed in four different ways:

1. In a preliminary analysis phase, the three cases were classified according to the five problem situation characteristics studied in the previous chapter. This allowed comparison to survey findings. In terms of the above analysis frameworks, this is best characterized as *hypothesis testing*, even though the 'hypotheses' merely consist of the loose propositions contained in the previous chapter.
2. Together with existing theory and the materials developed in previous chapters, the cases led to the development of a set of *practice-relevant issues* for describing and assessing the potential of OR applications (Section 9.6 in the guidelines on OR applicability). In Yin's (2003) terms, this best corresponds to *developing a case description*. In this thesis, the set of practice-relevant issues has helped describe the

most common types of OR applications in manufacturing logistics (Sections 9.7 through 9.13 in the guidelines).

3. The cases allowed a better understanding of *why* OR techniques were used. Problem situation characteristics could be identified that seemed likely to affect the applicability of the OR techniques employed. Such characteristics are crucial elements of the guidelines on OR applicability. This would be best characterized as *hypothesis generation*, even though the process was not as formal as in grounded theory. In Voss' terms (2009), it constitutes a simple *causal network*, since it attempts to identify variables (independent) that affect the applicability of OR techniques (dependent variable).
4. The cases improved the researcher's understanding of *how* three of the most common types of OR applications in manufacturing logistics typically are carried out. Based on this understanding, the researcher developed the general descriptions of these types of OR applications (Subsections 9.8.2, 9.9.3 and 9.10.4 in the guidelines). This way of using case evidence is again best characterized as *developing a case description*.

In conclusion, case data analysis played a crucial role in the development of the guidelines on OR applicability presented in the next chapter. Each case will now be presented.

8.2 Case 1: Felleskjøpet Trondheim uses deterministic optimization for plant location and distribution system design

This section presents the Felleskjøpet case. First, the problem situation is described, including some general information about the case company, logistics system characteristics as well as the decisions to be supported by OR. Thereafter, the factors that led Felleskjøpet to choose OR for decision support are discussed. Finally, the way the decision support was carried out and how it affected decision-making is scrutinized.

8.2.1 The problem situation

Felleskjøpet is the Norwegian co-operative for agricultural equipment. It is owned by Norwegian farmers and supplies them with feed concentrates, farm implements, commercial fertilizer, seed grain, pesticides and ensilage agents. Felleskjøpet's history dates back to the end of the 19th century, when farmers started to organize the purchase of operating equipment. Felleskjøpet consists of a number of regional co-operations. These regional units are independent legal and financial units which collectively cover the entire country. Until 2006, one of these units was *Felleskjøpet Trondheim*. It was the supplier of agricultural equipment to its 15000 owners in Middle and Northern Norway. In 2006, it had approximately 660 employees and an annual turnover of 2830 million NOK. On 1.1.2007, Felleskjøpet Trondheim merged with an other regional unit and became Felleskjøpet Agri.



The present case study focuses on the production and distribution of feed concentrates, which formed the backbone of Felleskjøpet's activities. Felleskjøpet Trondheim produced approximately 50 variants of feed concentrates, mainly for ruminants, swine and poultry. Producing feed concentrates is a blending process. The main ingredient in Norwegian feed concentrates is Norwegian grains. Other important ingredients include proteins, fat and soya flour.

Production was completely order-based (make-to-order) and closely coordinated with distribution for effective equipment utilization. Cost-effective transportation was important because transportation stood for a considerable part of the total product cost. Felleskjøpet's customers (and owners), the farmers, were highly concerned with costs because of cost pressures from their customers again, such as meat and dairy producers. In addition to cost minimization, delivery precision was important because the animals' lives depended on the feed concentrates. For these reasons, Felleskjøpet itself stood for transportation planning, i.e. the allocation of deliveries to vehicles and the detailed sequencing and scheduling. Feed concentrate was mainly transported in specialized vehicles only used for this purpose. Felleskjøpet had contracts with several transportation firms providing vehicles of different sizes.

Typically, the farmers would be given a discount if they left Felleskjøpet some flexibility in the delivery date or quantity. This allowed Felleskjøpet to better coordinate orders from different customers, achieving larger production series and better distribution routes. Production and transportation planning was collocated and in close contact with the transportation fleet and the customers.

Felleskjøpet had several production plants. Each produced some or all the different feed variants. Each had, for each variant it produced, a distribution area of farmers to be supplied. It was important that the same farmer always received a certain variant from the same plant because feed could taste different depending on where it was produced. Animals would respond to a change with reduced intake and performance. Since not all plants had the equipment to produce all feed variants, farmers could not always be replenished from the nearest plant. Generally, however, they strongly desired local production and would typically be resistant to plant shut downs, unless they led to significant cost reductions.

In 2001, Felleskjøpet Trondheim acquired a competitor (Stormøllen) and thereby increased the number of plants to six. Figure 8-2 shows where these plants were located. Four of them were around the Trondheim fjord, namely in Trondheim, Verdal, on the island Inderøya and at Steinkjer. In addition, there were plants in Overhalla and at Bergneset. Felleskjøpet Trondheim's maximum production capacity was then as high as 550'000 tons. The actual demand, however, was only around 300'000 tons, so there was considerable overcapacity. This suggested that it might be cost-effective to shut down some of the plants. More importantly, production at each plant was mostly adapted to its corresponding distribution area and not well coordinated with the other plants. For example, two nearby plants may each have produced a small amount of a certain feed variant, while centralized production at one plant would have been more cost-efficient. Also, some plants produced feed which could have been produced more cheaply at other plants. After the merger, these issues became particularly apparent and called for a redesign of the distribution areas.



Figure 8-2: Felleskjøpet Trondheim's six plants were located in Middle and Northern Norway.

In summary, the following questions needed to be addressed from a cost-minimizing perspective:

- Which variants should be produced at which plants?
- Which farms should be supplied from which plants?
- Should any plants be shut down?

8.2.2 Using deterministic optimization for decision support

Felleskjøpet had a pretty good feeling of how to effectively design its distribution areas and which plants were shut down candidates. It desired a quantitative cost analysis to confirm it. This kind of rigorous documentation was necessary to provide robust justification for the board (the owners), who had to give its approval. As explained, Felleskjøpet's owners were at the outset reluctant to shut downs. On the other hand, constant cost pressures from their customers necessitated them to seize any opportunity for cost reduction, ultimately leading to lower feed prices.

Felleskjøpet had previously carried out similar analyses. In 1999, for example, it calculated if the plant at Bergneset and any of the silos in Northern Norway could be shut down. This analysis had only a few feasible alternatives, for which the costs could be estimated by means of a descriptive 'spreadsheet' simulation.

This time, however, the number of alternatives was much higher. For each of six plants, it had to determine which variants to produce, and which customers to serve. Since the solution at one plant affected and depended on the other plants' solutions, the problem could not be subdivided into simpler parts and therefore had a daunting number of alternative solutions.

Felleskjøpet knew that in such situations, deterministic optimization could be a good analysis approach because it could automatically pick good solutions from all the available. Felleskjøpet already used optimization to determine optimal blending recipes for its feed concentrates, a typical application area of this technique. Moreover, the farmers were acquainted with and accepted this type of decision support because Gilde Norsk Kjøtt, the largest Norwegian meat producer, had previously used it for plant location and distribution system design. Like Gilde Norsk Kjøtt, Felleskjøpet chose to rely on SINTEF's modelling expertise. SINTEF is a well-known institution in Norway and a report prepared by SINTEF could critically affect the board's decision.

In summary, the researcher identified the following reasons why Felleskjøpet chose to use optimization for decision support:

- It desired a quantitative cost analysis that could confirm its 'gut feeling' of good plant configurations and distribution areas.
- A formal OR analysis carried out by SINTEF would provide a credible argument and help convince the board of the effectiveness of suggested structural changes.
- Due to cost pressures from dairy and meat producers, Felleskjøpet's customers attached high importance to cost reduction/minimization, which is the perspective taken by optimization.
- The problem could not be broken down into subproblems and therefore had a large number of alternative solutions, far too many to be analyzed in a 'spreadsheet' simulation.
- Felleskjøpet and its customer had previously been in contact with optimization and recognized it as an acceptable approach to decision support.

Note that the first two points refer to advantages of OR in general, the next two refer to problem situation characteristics that make optimization a good choice. The last also helps optimization succeed, but is not directly related to the problem situation of concern.

Still in 2001, SINTEF and Felleskjøpet therefore used optimization to address the above questions. The study consisted of model development, data collection and model analysis. Each of these three parts stood for approximately 1/3 of the total resource consumption, which was approximately two man-months. SINTEF could reuse elements of models it had developed earlier in similar projects (such as the one with Gilde Norsk Kjøtt), which speeded up model development.

The model for Felleskjøpet Trondheim had the following features:

- Farms were grouped according to postal codes. This gave a detailed representation of the geographical distribution of farms. It made calculation of transportation costs convenient, since Norwegian carriers often specify costs in terms of these postal codes.
- Demand was expressed by means of average yearly quantities per postal code.
- The 50 variants of feed concentrates were aggregated to six groups, two for ruminants, two for swine and two for poultry.

- The following input cost types were used:
 - Transportation costs from plants to farms: Unit transportation cost between any two postal codes. Where possible, these costs were based on actual transport contracts. Where no such contracts were available, contracts with similar terms and conditions were assumed.
 - Production costs: Unit production cost for each plant/variant combination
 - Fixed plant operating costs
 - Raw material and inbound transportation costs: These costs were included in the unit production cost (which was possible because blending recipes were considered as fixed).
- The model was a mixed-integer program (see Section 4.6). One particular feature was that production costs were expressed by a so-called piecewise linear function: Three different unit production costs were used depending on total production volume at a plant.
- The model sought the cost-minimizing trade-off between fixed plant costs, transportation costs and production costs, given production capacity limits.

SINTEF used the software system XPress-MP for modelling and analysis. XPress-MP contains a modelling language for model development (Mosel), a solver with solution algorithms (XPress) and functionality for model analysis.

Once SINTEF had developed the model and carried out a first analysis (optimization), the reasonableness of the model and its answers was discussed jointly with Felleskjøpet. The model had calculated that the best solution was to centralize production and only use the three plants which were not allowed to be closed down, namely Trondheim, Steinkjer and Bergneset. This confirmed Felleskjøpet's feeling, but was – at least in the short run – not a feasible solution. Felleskjøpet Trondheim therefore asked SINTEF to test various alternative scenarios, typically by forcing the model to operate certain plants and calculating optimal distribution areas given these requirements. In total, 12 different scenarios were investigated. The key elements of the study were included in a report, which was discussed internally by Felleskjøpet's management and submitted to the board.

Even though the model recommended closing down three plants, Felleskjøpet Trondheim's final decision was to keep all plants operating. This was due to qualitative considerations, which could not easily be included in the model. The plant on Inderøya, for example, was retained because otherwise, a competitor would have entered the region. More generally, it reflected the farmers' reluctance to plant shut downs. On the other hand, the model was very useful to design effective distribution areas. Moreover, it affected the long-term strategic direction Felleskjøpet chose in subsequent years. Indeed, when the researcher inquired about the plant structure at the beginning of 2011, production on Inderøya had been phased out.

In conclusion, Felleskjøpet Trondheim benefitted from optimization because it provided rational, quantitative documentation of cost-effective plant and distribution system configurations among a large number of alternatives. Other regional Felleskjøpet units used optimization for similar purposes.

8.3 Case 2: Gilde Norsk Kjøtt uses discrete-event simulation for production plant design and the determination of production rules/policies

The second case study concerned Gilde Norsk Kjøtt and how it used discrete-event simulation at one of its meat processing plants. The present section provides information about Gilde Norsk Kjøtt and the problem situation it faced, followed by a description of how discrete-event simulation was used for decision support.

8.3.1 The problem situation

The Norwegian meat co-operative is Norway's largest meat producer. It was called Gilde Norsk Kjøtt until autumn 2006, when it merged with Prior, a poultry producer, and was baptized Nortura. It was established by farmers around 1900 in order to vertically integrate the production of meat. Still today, it is owned by its suppliers, over 30'000 farmers all over Norway. The company headquarters are located at Løren in Oslo. In 2006, Nortura had approximately 6500 employees and a turnover of 15 milliards NOK. Nortura has 41 plants all across the country, whereof 27 are former Gilde Norsk Kjøtt plants. These plants have various functions within slaughtering, cutting, processing, packing, and warehousing. Recent years have witnessed increased specialization at these plants. Figure 8-3 shows one of Norturas meat cutting lines.



Figure 8-3: A meat cutting line (Picture: Atelier Klingwall, Nortura Forus)

The production plant considered in this case study is located at Steinkjer in Middle Norway. It is a former Gilde Norsk Kjøtt plant, was established in the 1960ies and was extended several times since then. The plant has specialized in the slaughtering, cutting and processing of pigs, which are supplied from farmers in Central Norway.

As is typical for the meat industry, the plant has a diverging material flow: A single type of raw material (pigs) is transformed into numerous stock keeping units (130 at the Steinkjer plant). Figure 8-4 shows the basic cuts of pork. Besides different cuts, factors increasing the number of stock keeping units include different treatments, qualities, and packing variants. Meat can either be fresh or frozen. Most stock keeping units produced at Steinkjer are transported to a different plant for further processing, but the plant also produces a number of consumer-packed finished goods.

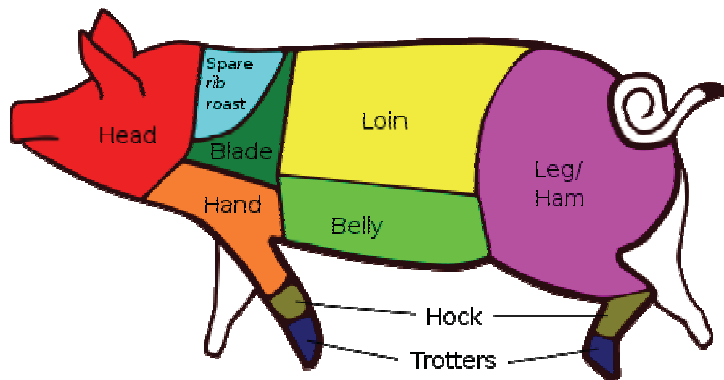


Figure 8-4: The basic cuts of pork

Figure 8-5 shows the main processes and material flows at the plant (very simplified). After slaughtering, carcasses are cut into various pieces according to a so-called *cutting pattern*. A cutting pattern specifies the proportion of finished stock keeping units to be cut (for example, 50% of legs left unbroken, 50% cut down into smaller pieces). Cutting patterns are determined by demand and forecasts. After cutting, certain pieces are processed, before they are packed and either frozen or shipped.

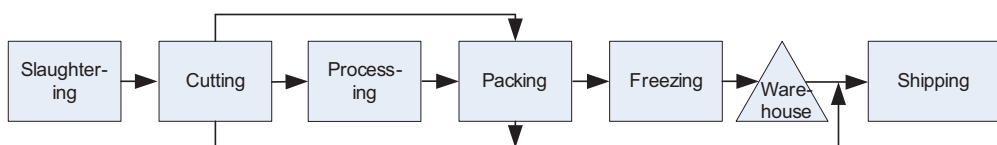


Figure 8-5: Main processes and material flows at Gilde Norsk Kjøtt's Steinkjer plant

In 2004, the plant had a capacity of 600 pigs per day. During 2005 and 2006 Gilde Norsk Kjøtt increased plant capacity to 800 pigs per day in a 9 million Euro investment. This involved large changes in the production system, such as new machines and material handling systems. It was of key importance that such investments were going to be utilized effectively, and that they actually resulted in the required increase in plant capacity from 600 to 800 pigs. Before purchasing and implementing any new equipment, there was therefore a need to predict its effects and to carefully plan its integration into the existing plant, which had to stay operative during plant extension.

More precisely, questions of the following type had to be addressed carefully:

- Is the daily target capacity of 800 pigs achieved with a proposed solution?
- Where are the bottlenecks?
- What is the level of utilization of operators and equipment (there might be a maximum level of allowed operator utilization)?
- What is the buffer size (floor area) needed in front of the different stations?
- Is adequate line balancing enough to assure a desired cutting pattern, or is more active control of material flows necessary?

This desire to predict the effects and estimate the performance of alternative future solutions for its Steinkjer plant was the problem situation Gilde faced.

8.3.2 Using discrete-event simulation for decision support

As explained in Chapter 3, quantitative analysis provides a good means to make such predictions and estimates. Gilde Norsk Kjøtt therefore asked SINTEF to help them correctly calculate required equipment capacities and assess how to effectively operate the plant.

As far as technique selection was concerned, it was quickly seen that discrete-event simulation was necessary to accurately model the complexities of the real system. The use of deterministic calculations was inadequate because of irregular arrivals of items. This irregularity was caused by merging material flows before shared resources, such as the conveyor belts in the cutting area and the machines in the packing process. Deterministic calculations ignore the fact that irregular item arrivals lead to queues. This type of randomness is well addressed by queuing theory and discrete-event simulation. The splits and merges in the system would, however, have been difficult to model by means of queuing theory.

This is why it was decided to use SINTEF's expertise in discrete-event simulation to help Gilde Norsk Kjøtt with the redesign of its Steinkjer plant. First, a discrete-event simulation model of the original plant was developed (in 2004). Thereafter, several detailed issues were analysed during 2005 and 2006. The discrete-event simulation model was developed and used in parallel with the design, implementation and launch of the actual plant. This parallel development provided the project team at any time with an updated model ready to analyse various issues. Some of them are now described. The description is based on Nyen's report (2007).

In order to develop a new solution for the freezing process and the warehouse after it, the initial intention was to use Quest's advanced 3D visualizations to analyse different area dispositions, layouts and material flows. However, minor model extensions made it possible to carry out quantitative simulation runs. This way, capacity-related issues at the sorting operation between the freezing process and the warehouse could be analysed. Sorting capacity depended on the lot sizes and control principles used in the packing process, which were therefore also addressed in the analysis (decision type 'determination of production rules/policies').

Gilde Norsk Kjøtt also needed to acquire new cutting lines (decision type ‘production plant design’). The discrete-event simulation model was used to test the proposed solutions from two different equipment suppliers. It allowed detailed, intuitive visualizations and it uncovered several weaknesses in the proposed solutions. The solution Gilde Norsk Kjøtt finally chose had 42 cutting stations on three lines. Carcasses were transported into the cutting hall on an overhead conveyor system, conveyor belts stood for transportation between cutting lines/stations. Cut items were rolled manually out of the cutting hall.

When all the required new equipment had been chosen, a detailed simulation model of the plant was developed, including control rules/policies. Figure 8-6 shows an overview of this model. The cutting hall is in the top left-hand corner of the building. Figure 8-7 shows a more detailed view of the hall.

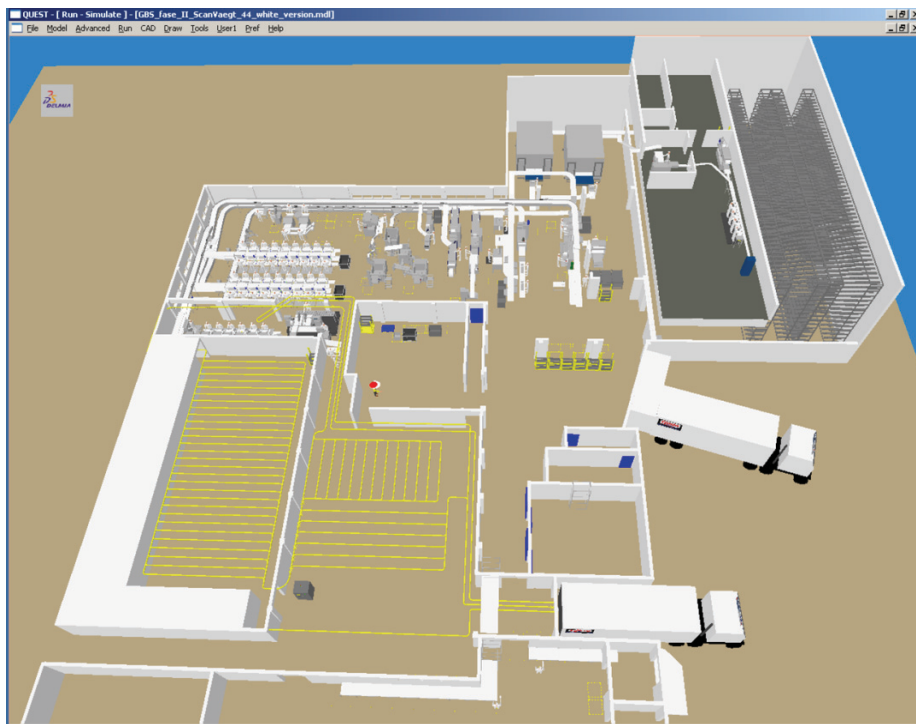


Figure 8-6: Overview of the discrete-event simulation model of Gilde Norsk Kjøtt’s plant at Steinkjer (Nyen 2007)

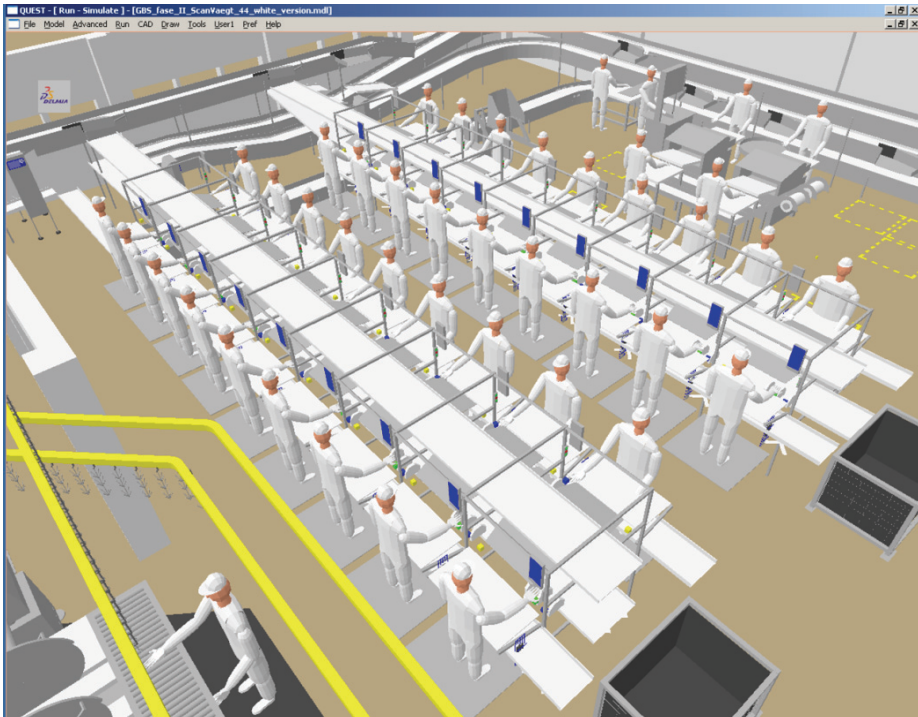


Figure 8-7: Detailed view of the cutting call (Nyen 2007)

This model was used to test plant capacity for two different cutting patterns. First, a cutting pattern corresponding to typical demand in 2006 was used. Thereafter, an expected future cutting pattern was used in order to see how well the cutting lines could tackle the change. Important input parameters in these simulations were:

- The cutting patterns
- Processing times (using first deterministic, thereafter stochastic values)
- Material flow control rules
- How the lines were balanced (i.e. which operations were to be carried out at which stations)

The main output parameters were:

- Throughput (i.e. the number of each stock keeping unit produced during a day)
- Queue lengths
- Operator/machine utilization

Output parameter values were used to address specific questions such as the ones listed above.

Note that uncertainty was addressed in two different ways in the simulation study. Uncertainty in operating times was modelled by means of probability distributions (normal distribution). Long-term uncertainty in demand levels was addressed by running simulations with two different cutting patterns, whereof one was a possible future pattern. For each pattern, plant performance could be assessed.

The total resources required for model development and use are estimated to lie between six and twelve man-months, but such estimations are difficult because model development and use was very integrated into other design and analysis tasks. The software system used was *Quest*, which has many features that are specific for simulations of production plants. It allows advanced 3D visualizations and animations.

For Gilde Norsk Kjøtt, the discrete-event simulation model constituted a new tool that supported the (re)design of one of its plants. It allowed 3D visualization of the existing as well as of the future plant, which increased management's and the operators' understanding of the model (as well as of the real system) and provided them with a better feeling of ownership of the model. It supported several decisions, both concerning the design of the plant and how to effectively control it. Even though the company does not own a licence of the software systems (Quest) and does not have the expertise necessary to develop or use discrete-event simulation models either, it intends to hire in such expertise again when (re)designing other plants. In conclusion, this case has illustrated how discrete-event simulation helped a manufacturing company design a production plant and assess various issues related to production control.

8.4 Case 3: Mustad tests multi-echelon inventory theory for safety stock calculations

The case company in the third case study was Mustad, the Norwegian manufacturer of fish hooks. In 2006, it struggled with high inventory levels across its global network of plants and warehouses. As a part of the ORIGO project, SINTEF and Mustad pilot tested multi-echelon inventory theory because the characteristics of Mustad's problem situations seemed amenable to this type of OR application. This section again first describes Mustad and the problem situation it faced, followed by a discussion of how a multi-echelon inventory system was tested and what was learnt from it.

8.4.1 The problem situation

O. Mustad & Son A. S. is the largest manufacturer and supplier of fish hooks worldwide. Mustad's history goes back to 1832, when Hans Skikkelstad established a company manufacturing nails and other metal products at Gjøvik in Norway. About half a century later, his son-in-law was running the company and explored the opportunities of manufacturing fish hooks. Together with his son, Hans Mustad, he founded Mustad & Son A. S. Since then, Mustad has opened numerous subsidiaries all around the globe. The sites of these subsidiaries have specialized roles in manufacturing, assembly, packing, distribution, sales, and marketing, or a combination of them. Figure 8-8 shows the locations of Mustad sites (at the end of 2006). The Mustad Group has approximately 1000 employees; in 2007, external sales were 300 million NOK. The company

Mustad

BEST SELLING HOOK ON THE PLANET



headquarter is located at Gjøvik. (This paragraph, including Figure 8-8, is based on Bakås et al. (2006)).



Figure 8-8: Sites of the Mustad Group at the end of 2006 (based on Bakås et al. 2006)

Fish hooks are characterized by small sizes, large volumes and many variants. Mustad’s product spectre consists of about 6400 different fish hooks (bulk variants), sold as in total approximately 12000 packed stock keeping units. The high number of different fish hooks is due to a large set of different materials, sizes, forms and colours.

Figure 8-9 shows the main stages in the manufacturing process from raw wire to packed hooks. First, raw wire is drawn, before it is machined into pins, which are then hardened. The result is so-called ‘bright’ hooks. Bright hooks are surface-treated, which results into finished hooks in bulk. The final process is packing. Certain stock keeping units are assembled before they are packed. Packed hooks are often sold in the local market, but also sometimes moved to other Mustad plants around the world for distribution purposes.

On its way from raw wire to the external customer, a hook typically passed trough several of Mustad’s plants and warehouses. Hooks sold in the U.S., for example, were produced at Gjøvik, sent to the Dominican Republic for packing and then shipped to the two distribution centres in the U.S.

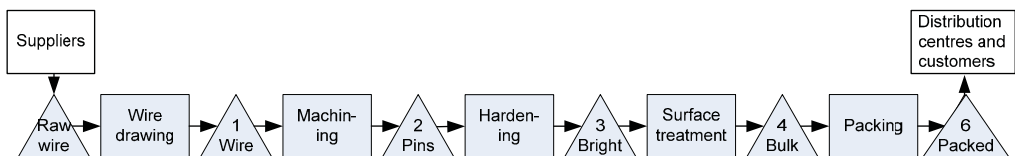


Figure 8-9: Mustad’s main manufacturing processes from raw wire to packed fish hooks

Mustad’s multi-stage production/distribution system has a diverging V-structure, where a relatively small number of variants at early production stages (approximately 80 variants after wire drawing) explode into over 12000 different stock keeping units of packed hooks. The

fact that packed hooks are often moved to several distribution centres further increases the number of Y-shaped splits as material flows downstream in the supply chain.

As for 2006, Mustad produced and packed all variants to stock, i.e. distribution centres held inventory of all items offered. Also at upstream stages in the supply chain, it kept inventory of most variants, i.e. wire, bright hooks, and bulk. If packing was done at a different location than production, both locations would typically keep a bulk inventory. Mustad managed the supply chain in a decentralized way, controlling each inventory using a simple (Q, R) policy: Whenever inventory levels fell to a reorder level R, an order of Q units was placed (for details, see Simchi-Levi et al. 2008). At each stock location, safety stocks were determined such that the location maintained a certain service level. As far as service level requirements were concerned, no distinction was made between internal customers (other Mustad sites) and external customers. There was no coordination of safety stock levels or service level targets across production stages and sites.

These characteristics of Mustad's logistics system had led to a large amount of inventory tied up at the different stages and sites. In particular, the total amount of safety stock was high due to:

- A large number of different stock keeping units
- Safety stocks held at numerous sites and production stages
- Long lead times in production and especially in transportation between sites
- No coordination of safety stocks across stages and sites

In 2006, the average throughput time of hooks (from raw wire to sales of packed hooks) was in the order of 6 months. As a consequence of such high inventory levels, Mustad had high inventory carrying costs. Moreover, despite high inventory levels, Mustad often did not achieve set service level targets (in terms of product availability).

Mustad therefore desired to reduce the total amount of inventory in its supply chain while maintaining or improving product availability. It wanted to review the following decisions:

- Which items should be stored at which sites and between which production stages?
- If safety stock was to be kept of a certain item at a certain location, how much should be kept in order to achieve a given service level at lowest cost? Note that only service levels to external customers are really relevant because service levels between Mustad sites do not directly affect customer satisfaction.
- What are the effects on inventory costs from various changes in the supply chain, such as using air freight instead of sea freight?

Given the high amounts of inventory and associated costs in Mustad's supply chain, it was likely that focus on these questions could lead to substantial savings.

8.4.2 Assessing the potential of multi-echelon inventory theory for decision support

As a part of a larger research project (ORIGO), Mustad therefore approached SINTEF with the above questions. SINTEF had developed spreadsheet-based cost models of supply chains

before, but such models usually estimated safety stock requirements separately for each location. Mustad's challenge, however, was to determine how much safety stock to keep at each location so that a desired service level *to external customers* was achieved with as little inventory as possible in the supply chain *as a whole*. This is precisely the issue addressed by multi-echelon inventory theory (see Subsection 5.3.4). It was therefore decided to assess the potential of a multi-echelon inventory management system. The reasons why a multi-echelon inventory system seemed appropriate can be summarized as follows:

- Mustad had a *multi-stage* production/distribution system, where production, packing and distribution of the same hook could occur at three geographically different locations.
- Between each production stage, the hooks were stored and safety stocks were kept in order to make sure materials were available when the next stage required them. The distribution centres kept their safety stocks of finished goods.
- Large total amount of safety stock due to a wide product spectre, long lead times and many stock locations.
- Mustad was about to implement a *Global Control Centre* at Gjøvik, from where certain control-related issues should be coordinated for the entire global supply chain (Dreyer et al. 2009). Safety stock levels were considered as such an issue.

Several vendors of multi-echelon inventory systems were contacted and a list of selection criteria was used to select an appropriate system. Eventually, Optiant Inc.'s flagship product *PowerChain Inventory* was selected. Note that Optiant was acquired by Logility in March 2010 and its products, including *PowerChain Inventory*, are now part of the Logility Voyager Solution (www.pnewswire.com). It had the following advantages:



- Focus on multi-stage manufacturing
- Based on recent research at Massachusetts Institute of Technology (MIT)
- Ease-of-use for business users
- Details about *PowerChain Inventory* published in research literature (Billington et al. 2004)
- Optiant staff competent and pleasant

A pilot application was carried out with one bright variant and all the downstream items obtained from this variant (in total 11 packed stock keeping units). Input data included sales data and forecasts, lead times, process costs, inventory carrying costs and service level targets. Essentially, Mustad was responsible for data collection, Optiant did the modelling and SINTEF validated the results. Time requirements for the test case were estimated to about 4 man-weeks.

The pilot application led to several insights and conclusions about the use of multi-echelon inventory theory in general and for Mustad in particular. The following requirements were identified if a company is to benefit from this type of mathematical decision support:

(1) *Reorder points are to be strictly adhered:* Typically, inventory management systems suggest reorder points/times and quantities to planners, who are to make a final decision based on these suggestions. When the traditional, single-stage inventory models are used, the planners can adjust the models' recommendations based on their experience and market knowledge, thereby achieving better performance than if the calculated numbers had been followed uncritically. With multi-echelon inventory control, the situation is different. Planners are required to respect the timings and quantities calculated by the system, even though they can seem flawed or irrational. This is because from a local perspective, it is not possible to see what is best for the supply chain as a whole. Only when planners understand how multi-echelon theory works and are willing to follow its rules, it can be used beneficially.

(2) *The company must have a well-elaborated customer service strategy,* specifying service levels (in terms of product availability) and delivery time targets for different markets, customer types and product segments. Since service level and delivery time targets are key input data required by multi-echelon inventory theory, the company must agree on them before it can be used. Agreeing on such a customer service strategy can, however, be itself a challenging, strategic decision-making process.

Only when these issues have been adequately dealt with, a company is mature enough to benefit from multi-echelon inventory theory. As far as Mustad was concerned, for example, these requirements were not fully satisfied. The company had to solve these issues before it could take the use of *PowerChain Inventory* any further.

The second general insight was that even though inventory theory can model operational fluctuations and uncertainties by means of probability distributions, the models may not accurately enough represent the real-world system. For example, most of them assume that demand during replenishment lead time follows a normal distribution. For high-volume products with frequent orders, such an assumption is usually justified. If orders are infrequent, however, this assumption is violated; in such situations, there would typically be a small chance that an order arrives during replenishment lead time. Models assuming normally distributed demand would in these cases typically calculate safety stock levels that are too low to cover any complete order. Such safety stocks would, of course, be of little use. Mustad, for example, had thousands of low-volume variants which were typically ordered infrequently, but in relatively large quantities. The conclusion from this insight applies to OR applications more generally: It must be critically assessed, in each particular situation, if the assumptions made by the models provide meaningful results.

If the company is mature and the models sufficiently accurate, multi-echelon systems seem to have a considerable potential. The *Interfaces* survey bears witness to numerous successful applications. They can be used for both tactical and more operational determination of safety stock levels across the supply chain. For a given customer service level, their use leads to total inventory investments that are lower than if each location independently calculates safety stock requirements. Multi-echelon systems can also estimate the effect of different supply chain designs on inventory investments, such as transportation modes with different lead times. In conclusion, testing a state-of-the-art multi-echelon inventory management system in Mustad's global supply chain has given detailed insights into the applicability of such models/systems, whose use is expected to increase as companies become more mature and integrated.

8.5 Preliminary analysis

The previous sections provided detailed descriptions of this thesis' three cases. This section makes a first step in analyzing them by classifying them according to the five problem situation characteristics identified in Chapter 7 (Table 8-1). The remainder of the analysis is incorporated into the next chapter's guidelines on OR applicability.

Table 8-1: This table classifies the three cases according to their problem situation characteristics and the OR techniques used.

Case	Problem situation characteristics					OR technique
	Decision type	Planning horizon	Logistics system scope	Company size	Industry	
Felleskjøpet Trondheim	Plant location and distribution system design	Strategic	Supply chain owned by a single organization	Large	Food manufacturing	Deterministic optimization
Gilde Norsk Kjøtt	Production plant design; determination of production rules/policies	Tactical/ Strategic	Plant	Large	Food manufacturing	Discrete-event simulation
Mustad	Inventory management	Tactical	Supply chain owned by a single organization	Large	Miscellaneous manufacturing	Multi-echelon inventory theory

The characterization of the cases in Table 8-1 can be used to provide some further empirical evidence of propositions and findings made in the previous chapter.

- (1) The strategic/tactical planning horizons underpin that the scope of OR is not restricted to operational decision-making, as claimed by some. Moreover, the fact that Felleskjøpet did not follow the model's conclusions (at least initially) illustrates well that strategic decisions are also heavily affected by many qualitative factors, and that they therefore cannot be taken based on models alone.
- (2) The case companies were large, i.e. they had over 500 employees. This is in accordance with survey findings that OR applications tend to be carried out in large companies.
- (3) As far as industry is concerned, the Gilde case is interesting because survey findings suggest that it constitutes a somewhat more atypical technique-industry combination (Discrete-event simulation in the food industry). It supports the researcher's conjecture: The paucity of discrete-event simulations in the food industry cannot be explained by limited applicability, but is more likely due to limited awareness of and familiarity with advanced decision support technologies at lower management levels. As stated before, it indicates numerous unexploited opportunities for OR-based improvements in technologically less advanced industries.

It is also worthwhile to repeat here that the three cases constitute instances of three of the five most frequently published types of OR applications in *Interfaces* (see Table 7-2). This further indicates that these three types indeed are popular in practice. In conclusion, the three cases are fully in agreement with findings and propositions made in the previous chapter.

8.6 Summary

The purpose of the present chapter has been to present three case studies of OR applications in manufacturing logistics. It follows up the previous chapter's surveys with more in-depth assessments of the situations in which OR techniques work well, as well as of how they support decision-making in these situations. Cases were selected such as to be typical, diverse and easily accessible. The three chosen cases covered three of four relevant OR techniques and four of seven relevant decision types, and they constituted instances of three of the five most frequently published types of OR applications (based on the *Interfaces* survey). As such, they provided a very purposeful sample. They allowed identifying numerous problem situation characteristics that affected the applicability of the techniques used. They were also found to be fully supporting the findings and propositions made in the previous chapter.

This completes part IV of this thesis, the collection and discussion of empirical evidence. Essentially, it consisted of a study of close to 200 OR applications in manufacturing logistics. It thereby fulfilled this thesis' second objective, to provide empirical evidence of the link between problem situation characteristics and OR usage/applicability. Moreover, it provided the researcher with the knowledge and empirical support necessary to achieve the third objective, the development of guidelines on OR applicability. The next part presents these guidelines and rounds the thesis off with some concluding remarks.

PART V - GUIDELINES AND CONCLUSIONS

This thesis' final part integrates all the knowledge reviewed and developed so far into a comprehensive overview of the applicability of OR in manufacturing logistics. It is presented as guidelines for logistics professionals in Chapter 9. Conclusions are presented in Chapter 10.

9 Guidelines on the applicability of OR in manufacturing logistics

'For what good science tries to eliminate, good art seeks to provoke – mystery, which is lethal to the one, and vital to the other.' (John Fowles)

'Quick start'

In order to be able to use the guidelines, it is sufficient to read Sections 9.1, 9.4 and 9.5.

This chapter is the result of the thesis' third objective: Explaining to people without OR background in which situations OR techniques are likely to be beneficial, and how they work. It is one of the most important chapters, integrating the concepts and perspectives from part II, the classifications and characterizations from part III and the empirical investigations from part IV into a comprehensive overview of the applicability of OR in manufacturing logistics. Its goal is to make people outside the field of OR understand what OR can be used for and how it works.

Before the actual guidelines are presented, their goal is explained in this chapter's first section, existing guidelines are reviewed in the second section and some methodological elements presented and discussed in the third section. The overall structure of the guidelines is presented in Section 9.4, guidance on how to use them Section 9.5. Section 9.6 introduces and motivates practice-relevant issues for describing and assessing the potential of OR models/techniques. They are used in Sections 9.7 to 9.13, which contain the actual guidelines. Section 9.14 reviews the MOMENT case, which was introduced in the Introduction chapter, in order to illustrate how this thesis could have contributed to more effective technique selection. Section 9.15, finally, summarizes the core elements of the guidelines.

9.1 Purpose

The purpose of the guidelines is to explain in which problem situations OR techniques can provide added value, and how. Given a problem situation, they help understand if OR techniques can provide useful decision support. More generally speaking, this chapter provides an *overview* of what OR has to offer in manufacturing logistics. It is mainly written for people who need to be aware of the opportunities of OR without being OR professionals. This includes decision-makers and consultants working with logistics. It also includes logistics researchers who take more qualitative approaches to the field. The present chapter can help them understand in which situations to collaborate with OR professionals. It is presented in a form and language that is relevant for practice, with the vocabulary of logistics professionals rather than mathematics and computer jargon. Still, the chapter can also be of interest to OR professionals, especially those new to the field, highlighting promising

application areas and containing references to numerous real-world applications described in the literature.

9.2 Literature review

Literature on the applicability of OR techniques has already been reviewed at several places in this thesis. The literature reviewed in Chapters 4 and 5 often concentrates on describing the different OR techniques' properties and the assumptions they make, only marginally relating their usefulness to different problem situation characteristics. The surveys reviewed in Chapter 7 studied the techniques' usage in different problem situations, but were typically restricted to just a few problem situation characteristics and did not result into explicit guidelines on OR applicability. This section concentrates on existing work that directly aimed to explicate the situations in which the various OR techniques could provide useful decision support, as well as how they work.

Murphy (2005b) presents a checklist consisting of 9 questions that are relevant when selecting appropriate OR techniques (Table 9-1). Each of the questions addresses a problem situation characteristic. In most cases, two alternative answers are proposed; for each answer, an appropriate modelling technique is proposed. Murphy (2005b) stresses the value of refining this checklist based on a stream of practice papers and on interviews with their authors.

Table 9-1: Murphy's checklist (2005b) for choosing OR techniques

(1) Is the issue one of choice based on values or determining actions to solve a problem? If it is choice, use decision analysis. Otherwise, continue.
(2) Are you choosing among many or few decisions? Having many decisions usually leads to a mathematical program that coordinates the myriad decisions. If the choices are few, simulation can be useful. If the choices are simple and randomness does not dominate, a spreadsheet may be sufficient.
(3) How complex is the situation? If it is very complex, you must understand this complexity and abstract the situation into connected smaller problems. You may need a multimodel approach.
(4) Do the actions of another person or other persons affect the value of your choices, and do your decisions affect them? If so, the situation may be a game.
(5) Is the outcome affected by aggregates of population? If so, you must represent the effect of the aggregate responses, as in econometric and economic equilibrium models.
(6) Is coordination central to making a good decision or good decisions? If yes, either a systems analysis or a mathematical program would be useful.
(7) Are randomness and uncertainty important? If yes, must the decision(s) be robust in the face of uncertainty, and is there no recourse to the uncertain outcomes? A scenario analysis using a deterministic model is probably sufficient. If yes, and the decision can be adjusted as more is learned, then a stochastic program or dynamic program could be the right model. Are few choices available? Then simulation can be a good tool.
(8) Are the choices discrete or can they be represented as continuous variables? The former situation leads to integer programming, unless the values of the integer variables are large and a continuous solution can be rounded into an integer solution.
(9) What is the time dimension? Are time stages important? If there are many time stages and few choices, consider dynamic programming or simulation. Time-staged linear programming works when you can ignore uncertainty.

This checklist reflects some of the technique characteristics discussed in Chapter 5 and provides a useful first appreciation of which technique(s) can be appropriate in a given situation. However, it concentrates on selecting among different OR techniques and does not help understand if a decision can benefit from OR at all. Moreover, there is a need to refine it, as the author emphasizes himself.

Mayo and Wichmann (2003) provide a one-page guidance on choosing between ‘spreadsheet’ simulation, [deterministic] optimization, discrete-event simulation and continuous simulation. The authors present a series of steps that help identify the technique that best fits a given problem situation. They emphasize the relevance of selecting the right technique for the right purpose, as well as of combining different techniques.

There are also a number of additional publications containing information on the link between manufacturing logistics problem situation characteristics and OR technique appropriateness, for example Alden et al. (2006) and Aleisa and Lin (2005). They are relevant for the present thesis and provided key input for the guidelines. In order to avoid repetitiveness, they are not presented in detail here, but used (and discussed) at relevant locations in the guidelines.

Besides, there are some publications with guidelines on technique selection in areas other than manufacturing logistics. Cooper et al. (2007) present guidelines on the choice of OR techniques for evaluating health care interventions. Ojala (1992) discusses the applicability of different OR techniques in port planning and analysis. In the area of forecasting, quite some work has been done supporting the selection of appropriate techniques, see for example Georgoff and Murdick (1986), Wheelwright and Makridakis (1980) and the seminal article by Chambers et al. (1971). Such work is not further considered here because it lies outside the scope of this thesis, but it has been used as a source of inspiration.

The work reviewed so far has been mainly written for OR practitioners. That is, it assumes that the readers are familiar with OR terminology and typically develop OR models themselves.

A number of publications aim at a wider audience and explain in plain language how OR techniques work. Especially the use of deterministic optimization for plant location and distribution system design has frequently been presented from a more managerial perspective. Already in 1976, Geoffrion (1976) described it without mathematical or computer jargon. He emphasized that a plain-language statement of the structural assumptions from which a model is fabricated, is a prerequisite for a manager to judge model validity and interpret its results. For a more recent example, see for example Simchi-Levi et al. (2008). Stadtler and Kilger’s (2005) book on APS systems provides managerial descriptions of how deterministic optimization is used to support also other decision types, for example short-term production planning.

While such managerial texts provide an understanding of how OR techniques work and help judging their appropriateness, they normally focus on one technique. This only provides a partial view and there is the danger that the applicability of this technique is exaggerated. There is a paucity of literature that addresses the fact that often, different techniques can support a certain decision type, that presents them all and that provides guidance on which technique to choose under which circumstances.

Bowersox et al. (2002) make an exception from this, in as much as they in Chapter 16 in their book describe alternative OR techniques for three types of decision within supply chain

management (Table 9-2). Of all the reviewed literature, their work most closely matches the guidelines developed in this chapter because it links OR techniques to problem situations and it is written from an operations management perspective, with focus on practice-relevant issues and omitting technical OR jargon. This chapter's guidelines can be considered as an extension of their work, including additional types of decisions, more specific links between problem situation characteristics and technique appropriateness, and a more detailed treatment of practice-relevant issues.

Table 9-2: Bowersox et al.'s (2002) link between decision types and analytical techniques (using Bowersox et al.'s terms, but indicating in brackets corresponding OR techniques as defined in this thesis)

Type of decision	Analytical technique
Location decisions	Mathematical programming [Deterministic optimization] Static simulation ['Spreadsheet' simulation]
Inventory decisions	Analytic inventory techniques [Inventory theory] Simulation inventory techniques [Discrete-event simulation]
Transportation decisions	Heuristic approaches, exact approaches [Deterministic optimization] Interactive approaches, combination approaches

Note that the empirical survey results in Chapter 7, Table 7-2, largely confirm Bowersox et al.'s links between decision types and (advanced) OR techniques. What these authors may not have been fully aware of in 2002, however, is that it can be difficult to make discrete-event simulations work in a supply chain context (See Subsection 7.4.3).

Summary of weaknesses

The publications reviewed in this section are steps into the right direction, and they provided useful input for the present guidelines. Nevertheless, they all have at least some of the following weaknesses:

- They are written from a perspective and in a language mainly relevant for OR professionals.
- They do not provide much guidance on which technique is useful under which circumstances, but concentrate on one technique and how it supports a certain decision type.
- They do not provide a comprehensive overview of OR technique usage in manufacturing logistics, covering all the important OR techniques and decision types.
- They are mainly based on experts' opinions and knowledge, with little empirical justification.

These weaknesses emphasize the need for additional work, which led to the guidelines presented in this chapter. The next section briefly explains how they were developed.

9.3 Methodology

The guidelines are the result of integrating and structuring knowledge on OR applicability. This section briefly explains where this knowledge comes from and discusses the development of the guidelines from a methodological perspective.

9.3.1 Data sources

As already shown in Figure 2-1, the knowledge contained in the guidelines originates from several sources. A key source was real-world OR applications. The surveys of *Interfaces* and the *Winter Simulation Conference* proceedings together constituted a total of 184 such applications. The three cases studies provided additional in-depth understanding. Developing knowledge on OR applicability by looking at real-world applications is a natural approach and has been suggested before. Murphy (2005b), for example, noted that ‘Developing a ... detailed checklist for choosing OR model types based on the stream of practice papers and on interviews with their authors would be a valuable research project.’

A second important source was existing literature, both empirical and conceptual/methodological. As the reviews in this thesis so far clearly have shown, various types of literature can be related to aspects of OR applicability, each making its own contribution to the topic. In particular, it must be emphasized that existing literature and theory has been used to strengthen the findings of this thesis’ surveys. The empirical basis for the guidelines is therefore much wider than the two surveys the researcher carried out himself.

Finally, the researcher could also draw upon his personal background and experience from working in projects at SINTEF, where the applicability of different OR techniques is a regularly recurring topic. Some interviews with relevant SINTEF researchers were also carried out. In conclusion, the guidelines are a synthesis of theory and data in a way considered as purposeful from the researcher’s perspective and experience.

9.3.2 Data analysis

The guidelines were developed by gathering relevant data and knowledge from the above sources, organizing it and presenting it largely without mathematical jargon. Turban and Aronson (2001) call the process of gathering, organizing and presenting knowledge *knowledge engineering*. Knowledge engineering accelerates the development of expertise in novices, and it constitutes a powerful and valuable way to assist decision-makers (Turban and Aronson 2001). Often, it results in so-called expert systems: Software tools whose objective is to transfer expertise from an expert to a computer system and then on to other humans (non-experts). This is what the guidelines do: Document and communicate expert knowledge on the applicability of OR techniques. As a matter of fact, much of the knowledge in the guidelines is likely to reside in some experts’ brains. Some of the value of the guidelines lies precisely in the fact that they make this often tacit knowledge explicit, easier to understand, and accessible to a wider community. This constitutes one type of knowledge developed in this thesis (see Subsection 2.3.1). Murphy (2005b) also recognized its value: ‘If we can document OR practitioners’ skills and expertise, we can codify their expertise, accelerate the development of expertise in people new to the profession, and better communicate what OR practitioners have to offer.’

In this sense, the guidelines can be considered as a practical tool for management. That is to say, this thesis’ third objective is not only concerned with developing knowledge and theory, but also with constructing an artefact aiming to improve managerial practice. Several

methodological research strands have proposed and examined an epistemological and methodological basis for this kind of practice-oriented, innovation-focused research. Kasanen et al. (1993), for example, proposed the *constructive approach* for problem solving through the construction of models, diagrams, plans and organizations. More recently, Holmström et al. (2009) and van Aken (2004), both building on Simon (1996), discuss the *design science approach* as a systematic approach to solving real-life problems and engaging in discovery. In design science, an artefact such as an organizational structure or a data system is designed, implemented in a real-world setting and tested, and its effects studied, typically by means of case studies (van Aken 2004). Both strands use the development of activity-based costing in management accounting as a typical example of this type of research. According to these authors, it is fundamentally different from the traditional theory building and theory testing approaches from the natural and social sciences (termed *explanatory science* by van Aken). While the latter seeks to explain how the world behaves (e.g. what is going on in manufacturing systems), the former aims to create or invent a new construct solving a real-world business problem.

The guidelines can be considered as such a construct. They could be tested and evaluated in practice, especially if they were implemented in an expert system. This testing and evaluation constitutes an important element in both the constructive approach and design science. However, focus in the present thesis has been more on gathering and organizing knowledge, and less on developing and testing a construct, such as an expert system, in the real world. This is why the researcher considers the guidelines to be more a result of knowledge engineering than of design science. Thus, while the development of the guidelines contains elements of constructive research and design science, it is mainly regarded as knowledge engineering resulting in a structured and ‘user-friendly’ collection of knowledge.

9.4 Overall structure

The overall structure of the guidelines is based on the classifications of OR techniques and decision types introduced in Chapters 5 and 6. As explained before, these classifications provide a useful framework for discussing OR technique applicability in manufacturing logistics because they cover the main decision types supported by OR as well as the main techniques used, and because different decision types are often supported by different OR techniques. The framework can be represented by the decision-technique matrix repeated in Figure 9-1.

		OR technique			
		Deterministic optimization	Discrete-event simulation	Queuing theory	Inventory theory
Decision type	Short-term production planning/scheduling				
	Plant location and distribution system design				
	Production plant design				
	Inventory management				
	Aggregate production and capacity planning				
	Determination of production rules/policies				
	Transportation management				

Figure 9-1: Scope and focus of the guidelines

The guidelines contain a separate section for each of the seven decision types. Each section discusses the applicability of OR techniques to support the corresponding decision type. In particular, it characterizes the problem situations that are likely to benefit from the different OR techniques. For the (advanced) techniques most frequently used to support a decision type, the guidelines contain descriptions of how they provide such support. These descriptions focus on the practice-relevant issues introduced and motivated in Section 9.6. The descriptions are very concise and merely intended to give a first, rough impression. They constitute general descriptions of typical OR applications in manufacturing logistics. Table 9-3 shows the complete content of the guidelines, with section/subsection and page numbers for the seven decision types and the descriptions of typical OR application. It helps users quickly orientate themselves and find sections relevant for the problem situation they seek support for.

Table 9-3: The overall structure of the guidelines with section and page numbers

	Section	Page
OR for short-term production planning/scheduling	9.7	192
Applicability of OR techniques	9.7.1	192
Deterministic optimization for big bucket and small bucket scheduling	9.7.2	197
Discrete-event simulation for testing of production plans/schedules and shop floor control	9.7.3	200
OR for plant location and distribution system design	9.8	201
Applicability of OR techniques	9.8.1	201
Deterministic optimization for network design	9.8.2	205
Discrete-event simulation to evaluate alternative supply chain designs	9.8.3	207
Inventory theory to assess the effect of different supply chain designs on inventory	9.10.2 – 4	220
OR for production plant design	9.9	209
Applicability of OR techniques	9.9.1	210
Queuing theory for analysis of serial production lines	9.9.2	213
Discrete-event simulation for analysis of more complex production systems	9.9.3	214
OR for inventory management	9.10	216
Applicability of OR techniques	9.10.1	217
Single-stage inventory theory for lot sizing	9.10.2	220
Single-stage inventory theory for safety stock decisions	9.10.3	221
Multi-echelon inventory theory for safety stock decisions	9.10.4	223
Discrete-event simulation for more tactical/strategic evaluation of inventory policies	9.8.3	207
OR for aggregate production and capacity planning	9.11	226
Applicability of OR techniques	9.11.1	226
Deterministic optimization for aggregate production and capacity planning	9.11.2	227
OR for the determination of production rules/policies	9.12	229
Applicability of OR techniques	9.12.1	229
Queuing theory for analysis of serial production lines	9.9.2	213
Discrete-event simulation for analysis of more complex production systems	9.9.3	214
OR for transportation management	9.13	231
Applicability of OR techniques	9.13.1	231
Single-stage inventory theory to determine shipment sizes from suppliers	9.10.2	220
Discrete-event simulation for tactical/strategic evaluation of transportation policies	9.8.3	207
Inventory theory to assess the effect of transportation lead times on safety stocks	9.10.3 – 4	221
Deterministic optimization for vehicle routing and scheduling	9.13.2	235

9.5 How to use the guidelines

Figure 9-2 explains how to use the guidelines. The starting point is a real-world problem situation in manufacturing logistics. First, it must be checked if it belongs to any of the seven decision types covered by the guidelines. If this is not the case, the problem situation is unlikely to be one typically supported by OR. If it is, closer investigation is necessary to determine if OR can provide added value. This can be done by reading respective section(s). Based on the understanding gained this way, the appropriateness of OR techniques can be better assessed. **It is sufficient to understand the section(s) relevant to the problem situation at hand; there is no need to read the entire guidelines.**

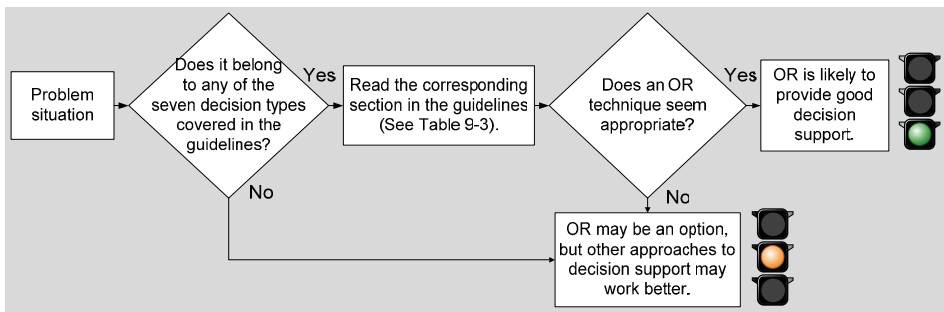


Figure 9-2: Flowchart explaining how to use the guidelines

Some clarifications and reservations must be made here. In order to base the guidelines on substantial empirical evidence, the researcher surveyed close to 200 OR applications described in the journal *Interfaces* and the proceedings of the *Winter Simulation Conference*. These surveys were presented in Chapter 7. Still, in order to avoid some repetitiveness in this thesis, parts of the discussion of survey findings are incorporated in the guidelines. The drawback of this organization is that the subsections on OR applicability can be perceived as somewhat lengthy.

It should be emphasized that, even though the guidelines are based on empirical evidence, they are not complete or undisputable truth. For example, OR techniques have been used in situations other than the ones described. Similarly, the descriptions of typical OR applications only contain some general observations; the detailed practicalities vary from case to case. The guidelines' reasonableness must therefore be critically assessed in each particular situation, and they can only be used as rules of thumb providing some first indications (This methodological limitation is also discussed in Subsection 10.4.2). It can often be worthwhile to consult subject experts for a more detailed assessment. Such subject experts include OR practitioners as well as logistics professionals who are experienced in applying OR.

It must also be repeated that the guidelines, as well as this thesis more generally, focus on the use of *sophisticated* OR models developed by OR professionals (see Section 1.5 for further details). No attempt is made to describe all the problem situations that can be supported by simple calculus and 'spreadsheet' simulations, which are used very frequently in most organizations. Such simple types of models are only mentioned where it would have been unnatural not to do so.

The larger the company, the more likely it can benefit from OR techniques. This can be used as a very general, first check of the applicability of OR in a given problem situation. Survey findings provide empirical evidence that successful OR applications tend to be carried out in large companies. Subsection 7.4.4 discussed this fact and presented some possible explanations. Large companies should definitely assess the opportunities of OR if they have not done so yet. For smaller companies, opportunities usually evolve around simple models, for example supporting inventory management.

9.6 Practice-relevant issues for understanding and selecting OR techniques

This section presents a set of practice-relevant issues concerning the use of OR techniques for decision support. It has been developed based on the study of OR applications performed in the empirical part of this thesis, existing theory reviewed in Section 4.11 and the characterization of OR techniques presented in Section 5.3. In addition, other texts describing how OR works in practice, such as Stadler and Kilger's book (2005), were used as a source of inspiration.

The set of practice-relevant issues offers a checklist for describing, understanding and selecting OR models and techniques for manufacturing logistics. This chapter's guidelines concentrate on these issues. In addition to the usage here, the checklist can facilitate communication between logistics professionals and OR professionals. It helps the former understand and express their needs and the latter present and propose OR models. This way, the suitability of OR techniques can be assessed in a systematic, comprehensive way.

The remainder of this section introduces these issues and emphasizes their practical importance.

(1) The specific decisions supported: An OR model/technique usually addresses a relatively small set of precisely defined questions, for example certain aspects of distribution system design or production planning. In modelling terms (see Section 4.2), they are given by the decision variables. In order to judge the appropriateness of the model/technique, it is of key importance to understand which specific decisions it supports. As explained in Sections 4.9 and 4.11, the decision is one of the two elements constituting the *problem situation*, which is a crucial factor affecting OR applicability.

(2) The logistics system characteristics that make an OR model/technique a good choice: The *logistics system characteristics* are the other element describing the problem situation (see Section 4.9), thus also crucially affecting OR applicability. In production plant design, for example, the complexity of the logistics system affects the choice between queuing theory and discrete-event simulation. Just *which* aspects of the problem situation are decisive for technique appropriateness depends on the decision type. Each decision type has its own set of relevant characteristics.

(3) Related decisions not directly supported: In order to further clarify which decisions are supported by a particular OR model/technique, it can be useful to stress related decisions that are *not* directly supported. When deterministic optimization is used for network design, for example, decisions related to safety stock locations and quantities are not addressed adequately. More general limitations of the technique may also be displayed, such as the fact that discrete-event simulation is mainly a descriptive technique (it does not calculate mathematically optimal solutions but evaluates solutions specified by the user). The

presentation of such limitations is necessary because users may mistakenly take certain features for granted.

(4) Input data requirements: Collection of the data needed by the model/technique is normally the decision-maker's responsibility. Data collection can be challenging (Render et al. 2008) and has been identified as a major difficulty in OR applications by several surveys (Chen and Wei 2002, Pappis and Dimopoulou 1995). It is therefore important to be aware of the type of data required.

(5) Essential trade-offs addressed: As explained in Section 3.2, an important issue in logistics is balancing trade-offs, for example the trade-off between order costs and inventory carrying costs. OR can help find the right balance in such trade-offs, but it may not address *all* the relevant trade-offs. It is therefore important to be aware of just *which* exact trade-offs a given model/technique addresses. This also helps understand which performance measures the use of the OR technique typically improves.

(6) Assumptions: OR models are simplifications of real logistics systems. It is important to be aware of simplifying assumptions when assessing the accuracy and usefulness of an OR model/technique. Decision-makers must assess if they hold with sufficient accuracy for the real system, otherwise model results will not be of practical relevance.

(7) Consideration of uncertainty: Different OR models/techniques have different ways of coping with the fact that input data is uncertain. Some techniques use probability distributions to express operational uncertainties in, for example, demand or lead times. Others use only deterministic input data, and uncertainty is addressed by varying input data manually and looking at the effect on output parameters. Such *what-if analyses* are, for example, carried out with data that is difficult to estimate, such as certain cost types. *Sensitivity analysis* investigates how much input data can change before the solution changes.

(8) Procedures used to determine solutions: The procedures used to determine 'good' or 'optimal' solutions vary with the OR models/techniques. Sometimes, mathematical procedures (formulae or algorithms) automatically calculate good/optimal solutions (given the model's assumptions). In discrete-event simulation, good solutions must normally be identified by running various alternatives and comparing them.

(9) The use of the model/technique in the decision-making process: It is important to understand how the use of OR is integrated in the decision-making process. A central question is who interacts with the model. In some cases, models are implemented in user-friendly data tools that can be used directly by decision-makers. This is often the case when operational decisions are supported. In more strategic situations, OR models are often handled by OR professionals, who analyze questions asked by the decision-makers and communicate results. The degree to which model results affect the final decision also depends on the nature of the decision.

(10) Software requirements: The type of software systems needed to implement OR models also depends on the problem situation addressed and on the OR technique employed. They range from spreadsheets and ERP-system add-ons to sophisticated modelling packages requiring advanced mathematical and software expertise. In some cases, standard solutions can be used with limited customisation. In many cases, however, company-specific solutions have to be developed. The more complex and customized the software needs to be, the more it will normally cost. Logistics professionals therefore need to be aware of its role and use.

(11) Time and resources required for model development: Initial model development will take some time. Obviously, there is no point in using OR if a solution is required before a model is ready. Model development can be expensive. An OR analysis is only beneficial if the expected benefits outweigh expected costs. Logistics professionals need to be aware of the different costs, including model development, software development/licences, integration with existing systems, training etc. The type and level of required expertise also varies with the different models and techniques.

(12) Time and resources required for model use: Once an OR model is developed and implemented, it is ready to be used for decision support. The time and resources needed for model use also vary. They are typically lower for OR models employed directly by decision-makers. If specialized OR professionals need to manipulate the models, decision-makers will often have to wait some time before they receive the answers to their questions. Note, however, that it can be more expensive to develop models and software if they are to be employed by end-users, and end-users may require considerable training.

(13) Application examples: Finally, in order to get a better understanding of how OR techniques support a specific problem situation, it can be useful to study past cases.

Everything is now in place to formulate the guidelines, which will be done in the next seven sections.

9.7 OR for short-term production planning/scheduling

This section is concerned with the use of OR techniques to support operational, short-term production planning/scheduling and control (the terms planning and scheduling are used interchangeably). Such tasks focus on how much to produce of what, when and by which resources, given resources and external demand requirements. First, the different techniques' applicability is discussed, with focus on the detailed problem situations in which they can be beneficial. Thereafter, the way they support decision-making is briefly described.

9.7.1 Applicability of OR techniques

The results of the survey of OR applications described in the journal *Interfaces* suggest that **deterministic optimization** is the most frequently used OR technique in short-term production planning/scheduling. Its use is therefore discussed first.

Deterministic optimization can be used in several problem situations. Stadtler's big bucket scheduling and small bucket scheduling (2005b) are now briefly introduced as two general such situations. Examples from the *Interfaces* papers are also provided, even though these real-world applications do not normally fit neatly into one of the two scheduling situations.

Big bucket scheduling

In big bucket scheduling, time periods are shifts, days or weeks, and resources of similar functionality are grouped into resource groups. The task is to determine how much to process of each product in each time period and at each resource group. The result is a *capacity-feasible* short-term production schedule with a relatively short planning horizon, for example a week or a month. Note that big bucket schedules lack detailed granularity. They consider resource groups and relatively 'big' time periods. More than one set-up will normally take place at a resource group within one time period, and an operation started within a time period is also finished within that same period (Stadtler 2005b). Set-up times are not represented

explicitly; efficiency improvements with batch sizes can therefore not be determined either (Brown et al. 2002). Such detailed scheduling and sequencing at each machine needs to be done separately.

Deterministic optimization provides an alternative to material requirements planning (MRP). The advantage of using deterministic optimization is that it develops schedules that:

- respect resource constraints, such as limited capacity or input material
- Minimize costs, maximize profit or minimize some measure of time

Bixby et al. (2006), for example, present a model for scheduling meat processing operations which determines a cost-minimizing product mix. Bermon and Hood (1999) present a model that helps find a profit-maximizing product mix in the semiconductor industry. These two examples indicate that deterministic optimization often helps determine a product mix that makes optimal use of resources.

Big bucket scheduling models can concern either a single plant (such as Bixby et al. 2006 and Bermon and Hood 1999) or a supply chain. In the latter situation, deterministic optimization is used to develop supply chain wide coordinated short-term production schedules. Seven of the 25 applications of deterministic optimization in short-term production planning/scheduling described in *Interfaces* concerned supply chains. They indicate that the technique can support such coordination in various industries and process types. Bowers and Agarwal (1995), for example, describe an application in the apparel industry, Denton et al. (2006) in the semiconductor industry. The applicability of deterministic optimization models for coordinated supply chain planning is also confirmed by the *Interfaces* survey's relatively high number of such models for tactical planning (see Section 9.11).

Based on the applications described in *Interfaces*, the following problem situation characteristics often seem to be present when deterministic optimization is used:

- A single production plant where resources of similar functionality are grouped into resource groups, or a network of plants, where centralized, coordinated short-term production planning/scheduling is desired
- Large-scale production with high capital investments (Denton et al. 2006)
- Many end items and large amounts of data more generally
- There is a need to determine a profit-/cost-optimal product mix
- Schedules are not subject to frequent changes due to unexpected events like changing order quantities or disruptions (Stadtler 2005b)
- Time-phased, centralized planning is feasible and can lead to substantial cost reductions.

These are merely observations; further research is required to characterize the situations in which deterministic optimization can successfully support big bucket scheduling.

Note that for coordinated short-term production planning/scheduling in supply chains, a second OR technique has also been used: **multi-echelon inventory theory**. De Kok et al. (2005) provide an example. As the authors note themselves, following this route implied

deviating from the dominant paradigm, which is deterministic optimization. See de Kok and Fransoo (2003) for a comparison of the two techniques in this context.

Small bucket scheduling

Small bucket scheduling assigns detailed work orders to individual resources (such as machines) and sequences them (application examples: Pradenas et al. 2006, Vandaele et al. 2000, Olson and Schniederjans 2000, Portugal 1997). Time periods are typically hours or shifts, the planning horizon for example a shift, a day or a week. The objective in models for small bucket scheduling is usually to minimize some measure of time, for example average lateness, rather than costs. Set-up times are explicitly taken into consideration, which is particularly useful when they are long and sequence-dependent (Bowers and Agarwal 2007, Katok and Ott 2000).

Job shop scheduling and flow shop scheduling are typical examples of small bucket scheduling. In job shop scheduling, there are m machines or work centres in a facility, and n jobs to be processed on these machines. Different jobs can have different processing sequences and different processing times. The task of job shop scheduling is to determine the sequence in which to process the jobs on the machines such that some objective is minimized, for example the time the last job is completed. In flow shop scheduling, the processing sequence is the same for all jobs, but the processing times can vary. The task is then to determine in which sequence to process the jobs. For further details, see for example Sule (2008).

OR literature contains hundreds of deterministic optimization models addressing job/flow shop scheduling. Jain and Meeran (1999) review job shop scheduling models. Numerous authors discuss the applicability of such models in practice, for example Gupta and Stafford (2006), McKay and Buzacott (2000) and Dudek et al. (1992). They agree that there is a large gap between academic solutions and the practices of real-world factories. Some researchers have attempted to identify characteristics that would predict in which situations optimization-based job shop scheduling would be successful or beneficial. McKay et al. (1988) suggest that the more attributes from the following list a shop had, the better its chances of being able to use deterministic optimization directly:

- A stable and well-understood simple manufacturing process
- Simple manufacturing goals which are not affected by hidden agendas
- Short cycle times so that work can start and finish without interruption
- Predictable and reliable set-up and processing times
- Known delivery quantities, delivery times and delivery qualities
- Long times between failures relative to cycle times, and short repair times
- Accurate and complete information on processing requirements and the status of the jobs in the computer

In order to fulfil the last requirement, Kjenstad (1998) remarks that the manufacturer should have an inventory management system and a shop floor control system (Management Executive System) in house and operational.

McKay and Buzacott (2000) later noted that a single large machine problem or a process situation would satisfy many of their conditions (note that from a planning perspective, a manufacturing line can be considered as a single machine). See Denizel et al. (2007) for an application in such a situation. In a typical dynamic job shop, however, there are many machines, many products and orders arriving as 'jobs' with quantities, requirements and due dates attached (McKay and Buzacott 2000). Such an environment does not normally have the characteristics listed above. McKay and Buzacott (2000) therefore concluded that analytical and algorithmic aids have limited benefits to a typical job shop. This conclusion agrees with Dudek et al. (1992), who observed that application of flow shop sequencing and scheduling in the chemical process industry appears to be much more prevalent than in other types of manufacturing. 'There appears to be limited applicability in traditional, as opposed to highly automated, manufacturing systems – even though many flowshop-sequencing researchers thought, perhaps, this was an area with numerous potential applications' (Dudek et al. 1992).

McKay and Buzacott's (2000) and Dudek et al.'s (1992) observations are confirmed by the *Interfaces* survey. None of the *Interfaces* papers describes an application of deterministic optimization in a traditional (non-automated) job/flow shop with many products, many machines and complex job routings. Thus, even though models in research literature often address this type of manufacturing operations, there appear to be few such applications.

There is also literature discussing the applicability of deterministic optimization to support production planning/scheduling more generally. Solberg (1989) identified and critically assessed three paradigms for research in production planning/scheduling, namely the optimization paradigm, the data processing paradigm and the control paradigm. Wiers (1997) reviewed the applicability of OR and artificial intelligence. Again, such research often concluded that there is a gap between academia and practice. Randhawa and McDowell (1990) observed that, while academia concentrated on rigorous mathematical analysis and optimization (i.e. finding the mathematically best solution), industry had generally focused on pragmatic approaches such as Just-In-Time, Material Requirements Planning and Optimized Production Technology. Solberg (1989) concluded that 'if the paradigms were new, one could say that the practitioners were not yet aware of the possibilities offered by the research results, or that the research communities had not yet articulated them well. However, after all these years, one is forced to a more definite conclusion, namely, that the paradigms do not adequately address some of the important aspects of real production planning and scheduling problems.'

The gap between academia and practice seems to be caused by several factors, including the following:

- In order to model and solve scheduling problems in a mathematically feasible way, they are greatly simplified. These simplifying assumptions reduce the applicability of OR techniques in practice (Wiers 1997).
- Theoretical research seems to be motivated by what researchers can achieve rather than what is important (Gupta and Stafford 2006).
- Even though many aspects of business practices are not included in models, there is a lack of scheduling research on interactive and integrative decision-making (Gupta and Stafford 2006). Too little emphasis is put on the human element which, however,

plays an essential role in the scheduling function (Wiers 1997). Optimization attempts to generate schedules automatically, while in practice, scheduling is normally interactive.

- The development of generic systems is difficult since each situation is very particular (McKay and Buzacott 2000). Generic systems are necessary, however, in order for the costs of using OR to be acceptable to a wider range of users.

Wiers (1997) summarized the weaknesses of theoretical models by means of a number of inadequately covered issues: robustness; dealing with complexity; performance measurement; organizational embedding; data availability and accuracy; and interaction with human scheduler. These weaknesses indicate areas for further research if the applicability of deterministic optimization is to be enhanced.

It must be emphasized that *Interfaces* bears witness to numerous real-world applications of deterministic optimization, suggesting that the literature reviewed here gives an all too negative impression. In the researcher's opinion, it should be mainly used to obtain a better understanding of how likely a particular situation can benefit from deterministic optimization, and as a warning that this type of OR application can be challenging.

In order to test production plans/schedules and for shop floor control, **discrete-event simulation** has sometimes been used. Both surveys of OR applications carried out as a part of this thesis confirm this. Discrete-event simulation models have been used to simulate production at high-speed (simulation runs) using a proposed production plan/schedule in order to verify its quality in terms of on-time completion, capacity feasibility, resource utilization and cost effectiveness (application example: Brinkley et al. 1998). It thereby also helps identify scheduling problems, accommodate rush orders and handle emergency situations. An alternative use is to simulate shop floor activities in the discrete-event simulation model at the same speed as on the shop floor and compare outputs. This way, irregularities on the shop floor can be tracked down by investigating discrepancies between real and simulated output (application example: Leachman et al. 2002).

When discrete-event simulation models are used for such operational tasks, they need to be very detailed. As a consequence, they can normally only cover a small area of a production plant, consisting of a limited number of resources and products (Strandhagen 1994). According to Lehtonen et al. (2003), simulation-based scheduling is a viable option when size and volumes are not large enough to justify deterministic optimization, because the former does not require making current production schedulers' knowledge explicit (whereas the latter does).

Table 9-4: The purposes of OR techniques used to support short-term production planning, scheduling and control

Technique	Purpose
Deterministic optimization	<p><i>Big bucket scheduling:</i> Develop a capacity-feasible short-term production schedule with relatively 'big' time periods and resources grouped. Find cost-effective product mix. Centrally coordinate short-term production schedules across several production plants.</p> <p><i>Small bucket scheduling:</i> Assign detailed work orders to individual resources and sequence them, considering set-up times explicitly. Typically used in highly automated flow shops, for example in the chemical industry.</p>
Discrete-event simulation	Test a proposed production plan/schedule in order to verify its quality in terms of on-time completion, capacity feasibility, resource utilization etc. Track down irregularities on the shop floor.

Table 9-4 summarizes the purposes of the discussed OR techniques. They can be combined to take advantage of their respective strengths. Typically, deterministic optimization would be used to develop a tentative schedule, discrete-event simulation to test and refine it (application example: Greenwood et al. 2005). The remainder of this section describes the techniques' use in more detail.

9.7.2 Deterministic optimization for big bucket and small bucket scheduling

This subsection briefly describes how deterministic optimization models are used to support big bucket and small bucket scheduling. Focus is on issues that are specific for these types of applications. For a more general description and characterization of deterministic optimization, see Subsection 5.3.1 and Section 5.4.

For big bucket scheduling, typical input data include (inspired by Stadtler 2005b):

- Locations, parts, bills of materials, routings and associated operating instructions, lot-sizing and priority rules, resource capacities and resource consumption, calendars and the amount of overtime or additional shifts to be used
- Due dates for orders to be delivered to the next downstream unit in the supply chain, availability of items from upstream units in the supply chain at different points in time, inventory and work-in-process levels
- Financial estimates, such as piecewise material and production costs, piecewise income and, possibly, penalties for capacity violations and unsatisfied demand

Based on these input data, various types of algorithms are used to calculate cost-minimizing or profit-maximizing schedules, often by seeking the best trade-off between resource costs, income and penalties. Intuitive visualizations are possible of the developed big bucket schedules. Figure 9-3 below shows an example for a resource group called 'Machining'.

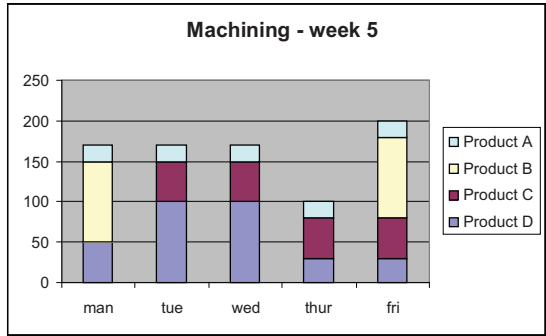


Figure 9-3: Example of a big bucket production schedule

For small bucket scheduling, input data include (again inspired by Stadtler 2005b):

- Resource capacities, processing times, bills of materials, routings and associated operating instructions, priority rules
- The set-up matrix specifying set-up times for all possible set-ups
- Work orders with due dates, inventory and work-in-process levels, set-up state of resources

Based on these data, the models arrange orders such as to minimize some measure of time, for example sum of lateness or sum of set-up times. Various, very different types of algorithms are used to do so. Due to computational limitations, they often do not determine a mathematically optimal solution, but calculate in reasonable time a satisfactory one (heuristic). This is often not a major drawback because all models are simplifications, and even an ‘optimal’ solution is only optimal within the simplified model world. Usually, managers aim to find a satisfactory solution, even if it may not be the best of all. The outcome is a time-phased schedule that can be represented by a Gantt chart (see Table 9-5 for an example).

Table 9-5: Example of a small bucket production schedule

Time of day	8	9	10	11	12	13	14	15	16
Machine A	P1	P1	P1		P5	P5			P3
Machine B	P7	P7	P7	P7	P7	P7	P8	P8	P8
Machine C	P2			P6	P6	P6		P9	P9

The remainder of this subsection applies to both big bucket and small bucket scheduling models. A good deal of assumptions and simplifications will normally be necessary. It is therefore important to assure that the models are accurate enough before they are used for decision support. Deterministic optimization models assume all data to be known with certainty; for example, demand is expressed as a given quantity per time period (or detailed

work orders). In order to account for uncertainty, the values of input parameters can be varied (such as demand or capacity levels) and the effect on the production schedule assessed (what-if analysis). Note, however, that in operational tasks such as scheduling, uncertainty is generally lower than in more strategic issues (In small bucket scheduling, for example, typically only confirmed work orders are considered). Moreover, new schedules are typically calculated frequently, considering the latest changes in input parameters such as demand and resource availability. This reduces the need for what-if analyses; it seems to work well even in uncertain environments (as the case by Bixby et al. 2006 shows, for example).

The following steps are typically carried out each time a new schedule is needed (based on Stadtler 2005b):

1. Gather relevant data, in particular information on demand, inventory/work-in-process levels and – in the small bucket case – set-up states.
2. Develop schedule using the deterministic optimization model.
3. Analyse schedule, if necessary adjust model and return to step 2.
4. Make manual adjustments if necessary.
5. Execute and update schedule until development of a new schedule is required.

In order to allow decision-makers use big/small bucket scheduling models themselves, they are often accompanied by user interfaces not requiring advanced mathematical knowledge. The models can thus be used without recourse to external analysts, which allows fast and effective use. One should be aware, however, that more complex models, with numerous decision variables and constraints, can take some time to be solved (i.e. to develop a schedule).

The models are implemented in different types of software systems. Big bucket scheduling models can often be developed and solved in general-purpose optimization packages. For very small models, spreadsheets and spreadsheet-based solvers can be used. The models and algorithms used for small bucket scheduling often need to be implemented by means of programming languages such as C++. In both cases, integration with databases and customized user interfaces are required. Advanced planning and scheduling (APS; see Section 4.7) systems provide standardized software modules for short-term production planning/scheduling. Although the success of APS systems has been limited, modules for short-term production planning seem to be among the more successful. For application examples, see Stadtler and Kilger (2005).

The time and resources needed to develop and implement models for short-term production planning/scheduling of course depend on the complexity of the problem situation. While in some simple cases, straightforward models and algorithms can be used, time/resource needs are often rather high. Advanced knowledge and experience in OR and database management is required, and previous experience with similar applications can be a considerable advantage. Integration with corporate databases, development of user interfaces and training of end-users further increase such needs.

For numerous application examples, see Appendix A. For further reading, see Stadtler (2005b).

9.7.3 Discrete-event simulation for testing of production plans/schedules and shop floor control

This subsection briefly describes how discrete-event simulation models are used to support short-term production planning/scheduling. Focus is on issues that are specific for this type of application. For a more general description and characterization of discrete-event simulation, see Subsection 5.3.2 and Section 5.4.

As explained, discrete-event simulation can be used to test tentative production schedules as well as to track down irregularities on the shop floor. Input data needs to be very detailed when discrete-event simulation is used at this planning level. It typically includes:

- Detailed machine and equipment characteristics, such as capacities and availabilities, set-up times and production rates
- Labour and machine maintenance calendars
- Work-in-process levels, set-up states, machine breakdowns, planned deliveries of purchased materials (this type of information is normally automatically transferred from the shop floor).
- The (tentative) production schedule(s)

Discrete-event simulation is very flexible and can incorporate many details of the production system, if this is deemed necessary. Even though it allows the use of probability distributions, input data is usually specified as fixed numbers. This is because in such operational planning, there is normally not much uncertainty left. Demand, for example, is given by confirmed orders that have already been released for production. If a random event such a machine failure occurs, a new schedule can be quickly generated and evaluated (Musselman et al. 2002).

Figure 9-4 illustrates the typical way of using discrete-event simulation in production scheduling (Strandhagen 1994). Based on order information and the state of the production system, a plan is created manually or with computerized support (for example deterministic optimization). This plan is then entered into the simulation model and production activities run at high-speed. The output of the model contains information about capacity utilization, delays, cost effectiveness etc., which can be used to evaluate and improve the plan. Several such loops may be required before a satisfactory plan is found. Feedback from production provides important input for the creation and evaluation of new plans.

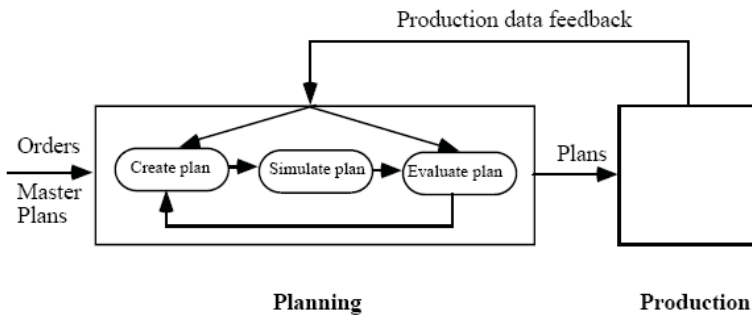


Figure 9-4: The use of discrete-event simulation in production scheduling (Strandhagen 1994)

Discrete-event simulation models can often be implemented by means of commercially available, visual interactive modelling systems. They often allow animated 3-dimensional visualizations, showing the movement of items in the production system. This feature has certainly contributed to the success of discrete-event simulation. A second opportunity for visualizations is graphs showing the development of output data over time.

Developing discrete-event simulation models is generally rather time-consuming. Skills in conceptual modelling, software implementation and model validation are necessary but often not available company-internally. Such models are therefore typically built by external consultants. Easy-to-use interfaces also need to be developed because simulation-based scheduling systems should be used directly by planners and therefore not require advanced simulation expertise (Strandhagen 1994). Once the models are implemented, however, the time it takes to run a simulation is normally short, which allows fast assessment of different schedules. Numerous application examples can be found in Appendices A and B.

9.8 OR for plant location and distribution system design

This section is concerned with the use of OR techniques to determine plant/warehouse locations and capacities as well as to design the distribution system. First, the different techniques' applicability is discussed, with focus on the detailed problem situations in which they can be beneficial. Thereafter, the way they support decision-making is briefly described.

9.8.1 Applicability of OR techniques

One of the most frequently cited manufacturing logistics problem situations supported by OR is *network design*. In network design, a set of at least two existing or potential future plants/warehouses is given, together with a number of delivery destinations (or customer areas). The problem is to determine aggregate material flows from suppliers to production plants to warehouses to customers, i.e. from which suppliers to replenish the production plants, from which production plants to replenish the warehouses, and from which warehouses to serve each customer. Transportation modes can also be selected as a part of network design. Once these material flows are given, the capacities required and product lines to be produced/stored at each location are also determined. Network design also determines if any existing plants should be expanded, reduced or closed down or if plants should be opened at some of the potential future locations. An additional issue that can be addressed within this context is what combination of public and private warehouse facilities should be used

(Bowersox et al. 2002). The need for network design often becomes particularly apparent after a merger.

Most papers on plant location and distribution system design published in *Interfaces* focus on network design. About half the applications considered production plants as given and concentrated on the distribution network.

The OR technique most frequently used in the applications described was **deterministic optimization**, more precisely **linear/mixed-integer programming**. This finding is as expected. The use of linear/mixed-integer programming for network design is well-known and explained in textbooks (Simchi-Levi et al. 2008, Chopra and Meindl 2007) as well as other literature (such as Goetschalckx and Fleischmann 2005). Already in the seventies, Geoffrion (1976) described it in a management-oriented way. This reflects the success of linear/mixed-integer programming to support network design, which is confirmed by the high number of applications in the *Interfaces* survey.

This success probably explains Ballou and Masters' finding (1999, 1993) that commercial software systems for facility location usually employ linear/mixed-integer programming, sometimes alongside with simple rules (heuristics) that guide problem solution. Similarly, it is probably one of the reasons why APS systems (See Section 4.7) often contain a strategic module for plant location and distribution system design based on linear/mixed-integer programming.

However, AMR research concluded in 2001 that the promises of APS systems were not realized (De Kok and Graves 2003). In the researcher's experience, this seems to be in particular the case for strategic APS modules. It seems that few have been sold to manufacturing companies; only occasionally, consultants use them for once-off analyses for a client.

This is not surprising given the strategic, one-of-a-kind nature of such strategic decisions. Only for very large companies, it would be worthwhile to purchase such a system for regular use. Moreover, the logistics system characteristics differ a lot from company to company, and even from business unit to business unit. This decreases the value of standard, off-the-shelf software because very much customization is normally necessary. De Kok and Graves (2003) note this for APS systems more generally. In addition, not all plant location and distribution system design issues need advanced techniques such as linear/mixed-integer programs (as discussed below). Thus, at least with hindsight, limited success of APS modules for plant location and distribution system design comes as no surprise.

Also Ballou and Master (1999, 1993) observed somewhat limited use of linear/mixed-integer programs in practice. In fact, their above-mentioned findings refer to OR techniques *implemented* in commercial software systems, not those actually *used*. When the same authors surveyed model users, it turned out that more than 75% of the firms that had purchased location models had selected simple rule-based approaches, i.e. spreadsheet-type cost models combined with some simple procedures that guide the selection of solutions (heuristics). These authors suggest that software systems might use linear/mixed-integer models because model developers perceive them as important, and not because they are most frequently used in practice.

For various reasons, surveys of OR practice in network design are likely to be somewhat biased towards linear/mixed-integer programming models. Ford et al. (1987) and House

(1978) found it to be the most frequently used OR technique. However, they only studied large companies, and large companies are more likely to have complex logistics networks that need and benefit from advanced OR techniques. The *Interfaces* survey is certainly biased towards advanced OR applications because the use of simple ‘spreadsheet’ simulation models is not normally reported in academic literature.

The conclusion from the discussion so far is that deterministic optimization clearly has a potential to support network design in practice, but that other, simpler techniques seem to be used frequently as well. As the following paragraphs show, technique appropriateness depends on the problem situation characteristics.

Linear/mixed-integer programming is often an appropriate technique when the number of alternative plant configurations is high, or when the best material flows for a given plant configuration are not easy to determine. The technique can *automatically* indicate choices that are cost-effective and respect given constraints, which is useful when there are a large number of alternative solutions. It can also reveal good solutions that were not expected. Its use will be described in more detail in the next subsection. For an application example, see the Felleskjøpet case in Section 8.2.

On the other hand, in many real-world contexts, especially in smaller companies, the number of different feasible and promising plant configurations and material flows is low. In such situations, spreadsheet-type cost models, in this thesis called ‘**spreadsheet**’ simulations, are often sufficient. ‘Spreadsheet’ simulation models can be used to analyze explicitly the costs and service performances of feasible and promising network configurations and compare them. Such models are normally cheaper, require often fewer simplifications and are usually more easily understood by non-experts than linear/mixed-integer programs. As mentioned, they are not only implemented in spreadsheets, but can also be found in application-specific commercial facility location software (see Ballou and Masters 1999 for examples). They are sometimes enhanced with simple heuristics that facilitate the search for good network configurations. Bowersox et al. (2002) present the typical heuristic procedure used, which starts from a network including all possible plant/warehouse locations and then iteratively eliminates locations until total costs do not decrease any more. As opposed to linear/mixed-integer programs, there is, however, no guarantee that the lowest-cost network is found this way. An alternative use of ‘spreadsheet’ simulation is to assess the performance of solutions recommended by linear/mixed-integer programs in more detail (application example: Laval et al. 2005).

Laval et al. (2005) further discuss the relative merits of the two techniques. Bookbinder et al. (1989) and Bookbinder (1984) show the usefulness of ‘spreadsheet’ simulation for network design and compare it to linear/mixed-integer programming. Both papers conclude that ‘in the right hands, either a [‘spreadsheet’] simulation or an optimization [linear/mixed-integer program] can be profitably applied to distribution problems’. What this conclusion seems to ignore, however, is that appropriate technique choice at least partly depends on the problem situation characteristics, in particular the number of alternative configurations.

Deterministic optimization and ‘spreadsheet’ simulation assume that the locations of potential future plants/warehouses are known. If this is not the case, **gravity location models** can be used to identify suitable geographic locations within a region. Such models minimize inbound transportation costs from suppliers as well as outbound transportation costs to customers. For further details, see Chopra and Meindl (2010).

The techniques discussed so far are all deterministic (input data is expressed by a fixed number) and often express costs as linear functions of product volumes. Certain elements of the logistics system, however, cannot be satisfactorily represented this way. Inventory requirements and costs, for example, are difficult to represent in linear/mixed-integer programs because they do not increase linearly with volume flows through a plant (Jimenez et al. 1998). The effect on stock outages of fluctuations in demand and lead times is not easily represented in deterministic models either (Shapiro 2001). Especially if demand fluctuates a lot, assuming that it is deterministic can give misleading results (Chwif et al. 2002).

Non-linear, stochastic OR techniques are therefore sometimes used for plant location and distribution system design as well. They are discussed in the next paragraphs. In the applications described in *Interfaces*, they were always used in combination with deterministic optimization, but they can also be used by themselves.

Discrete-event simulation models can be used to explicitly study how different control principles/parameters and operational uncertainties/fluctuations, such as in demand and lead times, affect supply chain costs and performance (application example: Karabakal et al. 2000). They can estimate supply chain costs for various configurations and scenarios, for example different lead times, different levels of demand fluctuations and different ways of controlling the supply chain. Thus, while optimization places most emphasis on the *structure* of the network, discrete-event simulation is particularly suitable for evaluating *control*-related issues and operational fluctuations/uncertainties. The decisions analyzed are often related to inventory policies, for example fixed order quantity vs. fixed order period, continuous vs. periodic review, reorder points and reorder quantities, as well as to transportation strategies, such as mode, quantities, frequencies, full truckload vs. less-than-truckload etc.

Discrete-event simulation is flexible and can model most types of supply chains. According to Chwif et al. (2002), it is particularly useful when there is high variation in demand, because a 'spreadsheet' simulation would lead to misleading results. It can also be useful when the effect of different control policies cannot appropriately be represented in a 'spreadsheet' simulation.

However, the development of discrete-event simulation for decision support at the supply chain level (several plants/warehouses) seems to be rather challenging. Especially the *Winter Simulation Conference* survey found few such applications. The difficulty to obtain detailed data, combined with the complexity of most supply chains, usually makes supply chain simulations very time- and resource-consuming. They also require expertise which is not easily available. Subsection 7.4.3 discussed the challenges of supply chain simulations in more detail. Supply chain simulations should only be endeavoured if there is ample time and resources. Relevant expertise should be available, access to detailed supply chain data should be easy, supply chain structures should not be in big transformation, and control policies should follow simple, well-behaved rules.

The effects of alternative network configurations on required inventory investments (safety stock and cycle stock) can also be estimated with models from **inventory theory** (Application example: Gupta et al. 2002). Such models are simpler and less detailed than discrete-event simulation models, but they still make realistic estimates of inventory costs and take into consideration the effects operational uncertainties, especially demand and lead time variations. In practice, they often provide estimates that are good enough. Simple, **single-stage inventory models** are often used in 'spreadsheet' simulations. If more resources are

available and there is a lot of inventory spread across different supply chain locations, **multi-echelon inventory theory** can be useful.

The techniques from the OR subfield **decision analysis**, such as decision trees, can also be used to support capacity decisions and network design. Such techniques can explicitly represent long-term uncertainties, e. g. uncertain future demand and prices. Since they are outside the scope of this thesis as defined in Section 1.5, the interested reader is referred to Chopra and Meindl (2010) for further details.

Table 9-6: The purposes of OR techniques used to support plant location and distribution system design

Technique	Purpose
Deterministic optimization	Select plants/warehouses from a given set of existing or potential future locations and determine aggregate material flows from suppliers through plants and warehouses to customers. High number of alternative solutions.
'Spreadsheet' simulation	As above, but with a smaller number of feasible and promising plant configurations and material flows. Also used to assess in detail configurations suggested by optimization.
Gravity location models	Identify suitable geographical locations within a region.
Discrete-event simulation	Assess the effect of different control principles and operational uncertainties/fluctuations on costs and performance.
Inventory theory	Assess the effect of different network designs on inventory investments.
Decision analysis	Quantify the impact that long-term uncertainties (demand, prices etc.) have on decisions related to capacities and network design.

Table 9-6 summarizes the purposes of the discussed OR techniques. Several techniques can be combined to take advantage of their respective strengths, such as deterministic optimization followed by discrete-event simulation (as suggested by Hax and Candea 1984). In practice, there is often not enough time and resources, however. The remainder of this section describes the use of deterministic optimization and discrete-event simulation for network design in more detail. The use of inventory theory will be described in Subsections 9.10.2 to 9.10.4.

9.8.2 Deterministic optimization for network design

This subsection briefly describes how linear/mixed-integer programs are used to support network design. Focus is on issues that are specific for this type of application. For a more general description and characterization of deterministic optimization, see Subsection 5.3.1 and Section 5.4.

As explained, deterministic optimization selects plants/warehouses from a given set of existing or potential future locations and determines aggregate material flows from suppliers through plants and warehouses to customers (Figure 9-5). It is useful when the problem situation has so many feasible alternative solutions that it would be impractical to analyse each of them separately in a 'spreadsheet' simulation.

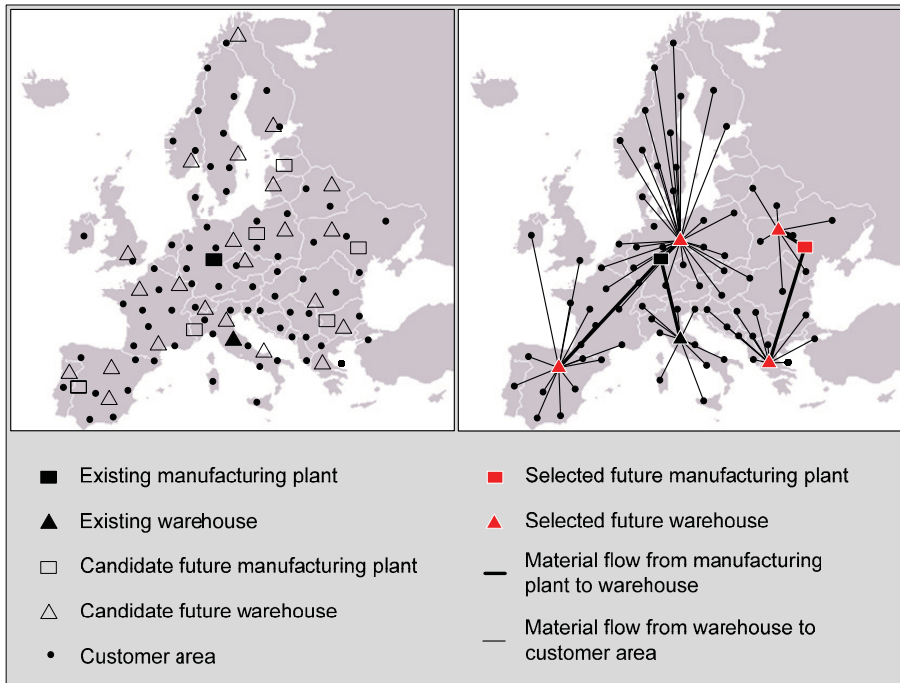


Figure 9-5: If there are a high number of alternative plant/warehouse configurations or material flows, deterministic optimization helps select cost-effective solutions.

The following input data are typically required in this type of OR application (based on Bowersox et al. 2002):

- Yearly/quarterly customer demand at each delivery destination (these will be aggregated into customer/market areas in the model)
- Product data, such as production requirements, distribution characteristics and channel arrangements (aggregated into product groups)
- The plants and warehouses (existing or potential future) to be included in the analysis. Suppliers, distributors, wholesalers, etc. may be included, but this makes the analysis more complex.
- Distances between sites and from sites to customers
- Fixed site costs, variable production/warehousing costs, variable inbound and outbound transportation costs, if desired including taxes and tariffs. These costs are usually assumed to be linear in product volume. Inventory costs are sometimes also assumed to be linear and included; as explained, however, assuming that they are linear is often unrealistic.
- Supply, production and warehouse capacity constraints per plant and product group

- Service level requirements, typically expressed as a maximum distance between plant/warehouse and delivery destination (Geoffrion 1976)

All these data are assumed to be known with certainty and expressed by fixed numbers. The relationships between the data are normally assumed to be linear; in particular, costs and capacity requirements are usually assumed to be linear (sometimes piecewise linear) in product volume.

Based on these input data and basic assumptions, the models calculate solutions that minimize total costs, i.e. they find the cost-minimizing trade-off between the different cost types, while respecting constraints related to capacities, service requirements etc. In order to account for uncertainty in input data, the models can specify how much the input data can change before the solution changes (sensitivity analysis). Various scenarios can be tested by changing input parameter values such as demand, costs and capacities (scenario analysis).

The type of software system required depends on the size and complexity of the particular model. Simple models can be solved with solvers available in spreadsheet software. Usually, however, general-purpose optimization packages are used. There are also specialized, commercial software systems for facility location, including the standard modules for network design in APS systems. However, as discussed, the success of the latter has been limited.

Usually, optimization models for network design are developed and used by company-external OR professionals because they require advanced knowledge and experience in OR and database management. This drives time- and resource requirements. Still, especially if the OR professionals have developed similar models before, smaller problems can be analyzed within some months.

Typically, the decision-makers define the problem and provide input data. The OR professionals then develop the model, make necessary model runs and report findings. Decision-makers analyse these findings and often return to the OR professionals with additional questions. This repeats until the decision-makers come to a satisfactory decision. Network design is strategic decision-making, which usually involves many qualitative considerations that cannot be included in a mathematical model. OR models constitute one element in a more comprehensive evaluation of available options. The Felleskjøpet case presented in Section 8.2 illustrates how more qualitative considerations can affect the decisions finally taken. For numerous additional application examples of deterministic optimization used for network design, see Appendix A.

9.8.3 Discrete-event simulation to evaluate alternative supply chain designs and inventory/transportation policies

This subsection briefly describes how discrete-event simulation models are used to evaluate supply chain design alternatives as well as inventory and transportation policies. Focus is on issues that are specific for this type of application. For a more general description and characterization of discrete-event simulation, see Subsection 5.3.2 and Section 5.4.

As explained, discrete-event simulation helps assess the effect of different control principles/parameters and operational uncertainties/fluctuations on supply chain costs and performance. Due to the complexity of most real-world supply chains, developing supply chain simulation models is usually rather challenging and should only be endeavoured if data and expertise are available and there is ample time and resources.

Input data is normally required at a rather detailed level. It includes:

- Structure of the supply chain, with suppliers, production plants, warehouses, cross-docking points and customers.
- Material and information links between the different supply chain nodes
- Decision rules and control policies used, such as order quantities, reorder points, transportation frequencies, full-truckload vs. less-than-truckload etc.
- Demand at each customer node, lead times at upstream nodes and between nodes
- Capacities and performances of resources
- Various cost elements if cost analysis is desired, for example unit production and transportation costs

In order to incorporate operational uncertainties and fluctuations, some of these input data can be expressed by means of probability distributions, for example demand, lead times and breakdowns. Demand may also be expressed by time series, i.e. actual customer order patterns.

Once a simulation model is developed, it can be used for tactical/strategic, off-line testing of different scenarios, such as different control principles and policies, different levels of fluctuations and different costs. It imitates supply chain activities as they evolve over time at high-speed by actually modelling entities being ordered, processed, transported and stored (simulation runs). When the simulation run is done, estimates (in the form of distributions, expected values, etc.) of various supply chain performance metrics are available, such as inventory levels, service levels, total costs, lead times and cycle times. Discrete-event simulation models do not directly suggest good solutions. The users themselves specify alternative solutions and compare their performances (estimated by separate simulation runs for each alternative). Other OR techniques can, however, be used to calculate promising solutions, which can then be simulated for more detailed assessment. For example, deterministic optimization can be used for network design (see Subsection 9.8.2), and inventory theory can be used to calculate good inventory parameter values (see Section 9.10). When this is done, the output of the latter techniques becomes the input to the former.

Different types of software systems are available. General-purpose discrete-event simulation tools, such as *Arena* or *Simul8*, have sometimes been used, but their success has been limited (Semini et al. 2006, Terzi and Cavalieri 2004). A number of tools specifically developed for supply chain simulations, such as *E-SCOR* and *Supply Chain Guru*, have appeared more recently. Again, however, few real-world cases have been reported in the literature (Semini et al. 2006). Spreadsheets can be used in very simple cases (one inventory, one product). Alternatively, computer programming languages such as C can be used, but this is more time-consuming. Thus, for the time being, it seems that fully appropriate software for supply chain simulations is yet to be developed.

Since discrete-event simulation represents a system as it evolves over time, it allows animated visualizations of supply chains, with material and information ‘items’ moving within and between processes and echelons in the supply chain (Figure 9-6). It can also draw graphs that show the development of output data over time, for example inventory levels.

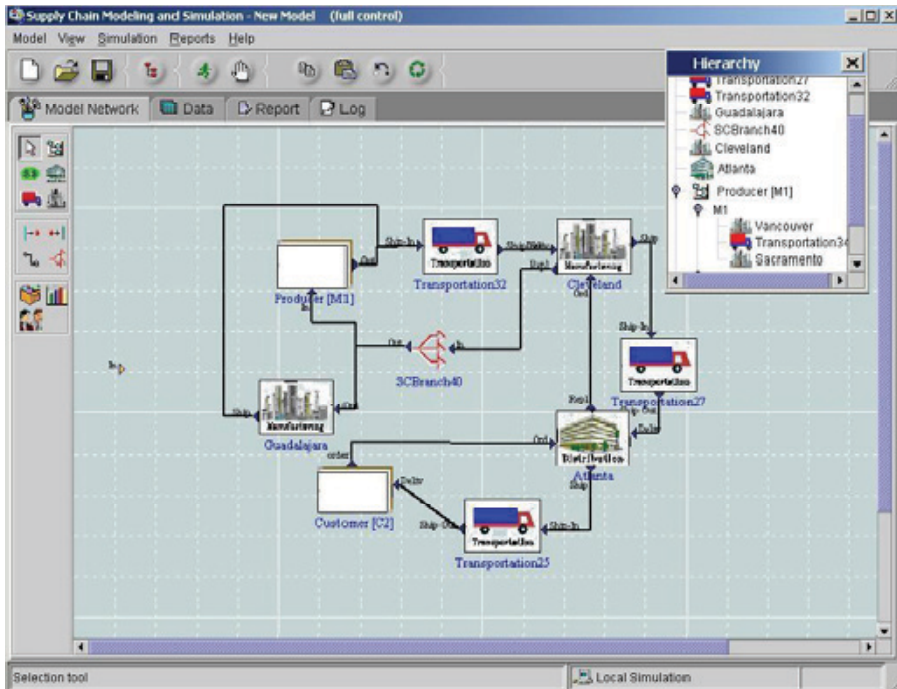


Figure 9-6: Example of a software system IBM has used for discrete-event simulation of supply chains (Xi et al. 2003).

Normally, discrete-event simulation models are manipulated by simulation experts. The decision-makers suggest various scenarios to these experts, who then carry out the necessary simulation runs and reports results back to the decision-makers. It should be emphasized that not only the development, but also the use of such models can be time-consuming. Each time a new scenario is to be analysed, new detailed data must be collected. Data collection is normally done manually in such tactical/strategic analyses, i.e. data are not automatically transferred from other corporate software systems. Actually running the simulation can also take some time, especially because the same scenario must be simulated several times (replicated runs) in order to achieve a desired level of statistical significance.

For application examples, see Appendices A and B. The following literature is recommended for further reading. Chwif et al. (2002), Banks et al. (2002) and Ingalls (1998) stress the value of discrete-event simulation for supply chain analysis. Bansal (2002) provides a somewhat more critical assessment. Terzi and Cavalieri (2004) review models and applications in the literature. Powell (2005) shows how to combine the technique with optimization.

9.9 OR for production plant design

This section is concerned with the use of OR techniques to design the layout and material flows within a production plant. Production plant design determines the number, capacities and required performances of physical resources (machines, workstations, operators, buffers etc.), their locations and the tasks they have to carry out. First, the different techniques' applicability is discussed, with focus on the detailed problem situations in which they can be beneficial. Thereafter, the way they support decision-making is briefly described.

9.9.1 Applicability of OR techniques

Among the 16 OR applications in production plant design identified in the survey of *Interfaces*, the most frequently used techniques were **discrete-event simulation** and **queuing theory**. Deterministic optimization was also used a few times. Inversely, surveys on discrete-event simulation usage in the manufacturing industry, including this thesis' *Winter Simulation Conference* survey and the survey by the Simulation Study Group (1991), indicate that production plant design is one of the main application areas of discrete-event simulation. The *Interfaces* survey also confirms this, and it indicates that production plant design is also one of the main application areas of queuing theory.

Discrete-event simulation and queuing theory models represent the inside of a production plant as a set of resources with material waiting in queues before these resources, being processed, and being moved to the next resource. If the buffer before a resource is empty, the resource is starved, if the buffer after is full, the resource is blocked. They are therefore particularly useful when the arrival of items before resources is irregular and leads to queues in the real system. In such situations, these techniques are not only useful for production plant design, but also to test production rules and policies. In many of the applications surveyed, the same basic discrete-event simulation or queuing model was used to support both decision types.

The characteristics of the problem situation determine which of these two techniques is most appropriate. If capacity and performance requirements of workstations and buffers are to be determined in simple, serial production/assembly lines (see Figure 9-7 below), queuing theory can be the right technique (Application example: Liberopoulos and Tsarouhas 2002). Developing relatively simple queuing models is usually not too time-consuming, they can provide quick results and allow testing line performances for numerous scenarios. In four of the seven cases described in *Interfaces*, models based on Gershwin's (1994) two-machine model were used. Often, these models were used to determine between which stations to place buffers, and which capacities these buffers should have. These seem to be typical questions addressed by queuing theory in practice. *Interfaces* survey results indicate that queuing theory is particularly popular in the automotive industry.

When queuing theory is used, the probability distributions of station times are usually considered as known (Boysen et al. 2008). So the technique presupposes that line balancing, i.e. the allocation of tasks to work stations, has been completed. The use of OR for line balancing is discussed below.

If the production system is more complex and includes, for example (based on Alden et al. 2006)

- multiple products with different processing flows
- queues with different, complex priority rules
- splits and merges with complex job-level routing policies
- carrier subsystems and closed-loop conveyances
- external sources of downtime that affect several disjoint workstations simultaneously

then the flexibility of discrete-event simulation is often required in order to achieve a sufficiently accurate model. All sorts of production systems can be simulated, such as production/assembly lines, job shops, material handling systems, production cells and flexible manufacturing systems. Typical users include the electronic and the automotive industries, and also batch-processing chemical/pharmaceutical plants regularly apply it. The flexibility of the technique should allow its use in most industries, however, which is confirmed by the *Winter Simulation Conference* survey (Table 7-5). For an application example in the food industry, see the Gilde Norsk Kjøtt case in Section 8.3, where the simulation model was developed and updated in parallel with the physical extension of the plant. In general, discrete-event simulation is often used when a new production plant is designed, as well as diagnostically to test various improvement ideas in existing plants. Developing realistic models is easiest if the production system consists of stable processes.

Discrete-event simulation can analyze many decisions related to production plant design and production rules/policies, such as

- Required number, capacities and performances of resources such as machines, workstations and operators, as well as the tasks they have to carry out.
- Alternative material flows and layouts
- Size and location of buffers
- Control mechanisms, lot sizes, priority rules, routing policies, cyclic schedules, work-in-process levels etc.

Alden et al. (2006) and Suri et al (1995) further compare queuing theory and discrete-event simulation in the context of production plant design.

Often, there is no time or need to develop an advanced OR model. Production plant design is certainly regularly supported by **'spreadsheet' simulations** and **factory physics principles**, even though the surveys carried out as a part of this doctorate study do not reflect this. Factory physics is a set of relatively simple mathematical formulae and more qualitative principles collected by Hopp and Spearman (2001). Such factory physics laws describe basic relationships in manufacturing systems. For example, the *conservation of material law* states that, over the long run, the rate out of a system will equal the rate in, less any yield loss. Factory physics laws can be used by themselves or in more advanced OR applications for verification/validation and other purposes. Standridge (2004) describes the latter use. It is reasonable to assume that such calculations and laws are frequently used in practice, but due to their simplicity, their use is not normally documented in literature.

As mentioned, **deterministic optimization** has also been used sometimes, for example in order to determine which resources to locate in which departments in the facility so as to minimize total cost of material movement (facility layout; application example: Denton et al. 2007). Since production plant design is also frequently supported by discrete-event simulation, the question of whether a facility layout study should precede simulation or vice-versa has received some interest. According to Aleisa and Lin (2005), optimization should precede simulation when the goal is to improve an existing layout, stochastic behaviour is insignificant, operational policies and production strategies are predefined and focus is primarily on minimizing travel distance and material handling costs. To this, it can be added that optimization is mainly useful if there is a large number of feasible layout configurations.

If the goal is to improve operational performance measures, such as minimizing flow congestions, or to justify policies and technologies in a system exhibiting significant stochastic behaviour, simulation should precede optimization. Their recommendations also help choose between the two techniques in a single-technique study.

A caveat must be made related to the use of deterministic calculations to determine capacity requirements and potential bottlenecks. Such calculations assume that items to be processed arrive at regular intervals. When orders/items arrive randomly, however, actual capacity requirements are usually much higher than those calculated deterministically; otherwise queues and lead times can become very long (In the example on page 105, queuing theory is used to show this). In such situations, the potential of deterministic models to calculate capacity requirements is therefore limited.

Research literature frequently uses deterministic optimization to address *line balancing*. Line balancing is the task of assigning operations to the different stations along a production or assembly line such that the workload is evenly distributed and precedence restrictions are fulfilled (Amen 2006). The goal of line balancing is to minimize the line's cycle time (Hanna and Newman 2001). Boysen et al. (2007), Becker and Scholl (2006) and Scholl and Becker (2006) survey and classify the research literature on line balancing models.

However, none of the surveyed *Interfaces* papers reported on the application of a deterministic optimization model to balance a real-world line. Many years ago, Hax and Candea (1984) and Chase and Aquilano (1973) already observed this gap between line balancing theory and practice. Recently, Boysen et al. (2008) again made similar conclusions. They found only 15 articles dealing with real-world assembly systems, compared to 312 research papers treated in the above-mentioned reviews. Their paper is interesting because it structures line balancing literature according to typical problem situation characteristics in practice, as such highlighting practice-relevant settings and providing guidance on which model to use in which situation. They found most applications to be in the automotive and appliance industries.

There can be several reasons why mathematical algorithms are not used more frequently for line balancing. Boysen et al. (2008) suggest that models and algorithms in the literature often do not correspond to the typical situations arising in the real-world. It must also be emphasized that it may not always be desirable to have a balanced line: Hopp and Spearman (2001) explain that the optimal configuration of most flow lines will be an unbalanced line. According to these authors, the typical line balancing problem is applicable only to *paced* assembly lines, i.e. lines where parts flow through zones on a belt or chain that moves at a constant speed, and one or several operators carry out specific tasks in each zone.

Thus, the applications of deterministic optimization in line balancing seem to evolve around certain specific situations. Note, however, that issues related to line balancing are sometimes addressed as part of a discrete-event simulation study (for example in the Gilde Norsk Kjøtt case). In the *Winter Simulation Conference* survey, line balancing was explicitly named three times.

Table 9-7: The purposes of OR techniques used to support production plant design

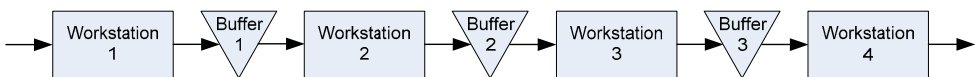
Technique	Purpose
Queuing theory	Determine required capacities and performances of workstations and buffers in simple, serial production/assembly lines
Discrete-event simulation	Determine the number, capacities and performances of resources, material flows and layout, location and size of buffers etc. in more complex production systems, with splits, merges, multiple products, complex priority rules, carrier subsystems etc.
'Spreadsheet' simulations and factory physics principles	Quick, rough calculations when there is no time or need for more detailed analysis. Also used in combination with more advanced techniques.
Deterministic optimization	Determine which resources to locate in which departments so as to minimize total cost of material movement. Balancing of certain types of production/assembly lines.

Table 9-7 summarizes the purposes of the discussed OR techniques. Several techniques can be combined to take advantage of their respective strengths, but in practice, there are often not enough time and resources. The remainder of this section describes the use of queuing theory and discrete-event simulation for production plant design in more detail.

9.9.2 Queuing theory for analysis of serial production lines

This subsection briefly describes how models from queuing theory are used to support production plant design and the determination of production rules/policies. Focus is on issues that are specific for this type of application. For a more general description and characterization of queuing theory, see Subsection 5.3.3 and Section 5.4.

As explained, queuing theory helps determine required capacities and performances of workstations and buffers, as well as lot sizes and work-in-process levels. It is mainly appropriate to model simple, serial production/assembly lines (Figure 9-7); more complex systems cannot usually be represented with sufficient accuracy.

**Figure 9-7: A simple, serial production line consists of workstations separated by buffers**

One of the advantages of queuing models is that they require little input data. Often they require little information beyond workstation speed, buffer sizes, lot sizes and machine failure/repair times. In order to account for uncertainty and fluctuations in such data, they are expressed by probability distributions. Note that no information about demand levels is normally entered into such models; instead, the cycle times they estimate indicate if a desired demand level is attained.

Once a queuing model of an existing or potential future line is developed, various alternative configurations and rules/policies can be tested. The model quickly estimates their performance in terms of cycle times, throughput times, capacity utilizations and work-in-

process levels (queue lengths). For example, the bottleneck in the production system can be identified and its capacity increased until the required cycle time is achieved or the bottleneck shifts. At a more operational level, the effect of planned lot sizes and work-in-process levels can be tested and plans adjusted until they are deemed good enough.

Normally, queuing models do not automatically recommend good values. The users themselves specify alternative solutions, and the queuing models then estimate their performance. Still, since queuing models provide results very quickly, a large number of alternative solutions can be tested within a reasonable time frame. Automatic or user-guided procedures can therefore be programmed that search for better and better solutions.

Queuing models have been implemented in software systems with user-friendly interfaces. Suri et al. (1995) discuss some of their development up to 1995. Today, software with the basic queuing models can be downloaded from the web for free. For more specific applications, spreadsheets, programming languages or mathematical software such as *Mathematica* are used.

Developing simple queuing models is often rather straightforward, especially with queuing software. More advanced, sophisticated models can take more time to be developed, and they require theoretical knowledge and experience. Once a model is developed, its use is normally easy and requires little advanced mathematical knowledge.

For numerous references to application papers, see Appendix A. For a textbook on queuing theory applied to manufacturing systems, see Gershwin (1994).

9.9.3 Discrete-event simulation for analysis of more complex production systems

This subsection briefly describes how discrete-event simulation models are used to support production plant design and the determination of production rules/policies. Focus is on issues that are specific for this type of application. For a more general description and characterization of discrete-event simulation, see Subsection 5.3.2 and Section 5.4.

As explained, discrete-event simulation can accurately model even complex production systems and helps determine various issues related to production plant design and production rules/policies. It is often used when a new plant is designed, or diagnostically to test improvement ideas in existing plants.

Input data requirements depend on how many details one desires to include in the model. Typical input data include:

- The configuration of the production system, with workstations, machines, operators, equipment and buffers
- Capacities and performances of these resources, in terms of processing times, set-up times, downtimes, buffer sizes etc.
- Size and capacities of pallets and transportation units
- Distances between resources
- Operational rules and policies for material flows, such bills of material and the process flows for each variant

- Demand, for example expressed as inter-arrival times of items to be processed

In order to incorporate operational uncertainties and fluctuations, input data can be expressed by means of probability distributions, in particular inter-arrival times of items, machine times, failure frequencies and repair times. Note that, as in queuing models, demand is often not explicitly entered in the discrete-event simulation models. Instead, the models estimate maximum output in terms of cycle times, which indicates if a desired demand level can be achieved.

Discrete-event simulation models are used for tactical/strategic, off-line testing of various scenarios and improvement ideas. For each scenario/solution, the model imitates production activities as they evolve over time at high-speed by actually modelling entities waiting before machines, being processes and moving on (simulation runs). This way, the performance of alternative system configurations and control rules/policies is estimated in terms of capacity utilization, cycle times, throughput times, waiting times, work-in-process levels (queue lengths) etc. Different alternatives can be compared and a better understanding of the real system is thereby obtained.

Discrete-event simulation models do not directly suggest good solutions. The users themselves specify alternative solutions and compare their performances (estimated by separate simulation runs for each alternative). Other OR techniques, such as deterministic optimization or factory physics principles, can be used to calculate promising solutions, which can then be assessed in detail in the simulation model. In such applications, the output of the former techniques becomes the input for the latter.

As explained, analysis of production systems (within a plant) is one of the main application areas of discrete-event simulation. It is therefore not surprising that many commercial discrete-event simulation software systems are well-adapted to this application area, with predefined symbols and other specific features. They work well in most cases, so that the need to resort to programming languages is rare today.

They often allow animated 3-dimensional visualizations, showing the movement of items in the production system (Figure 9-8). This feature has certainly contributed to the success of discrete-event simulation. It improves communication between simulation expert and decision-maker, and it provides an intuitive way to validate simulation models. A second opportunity for visualization is graphs showing the development over time of output data, such as queue lengths or machine utilization.

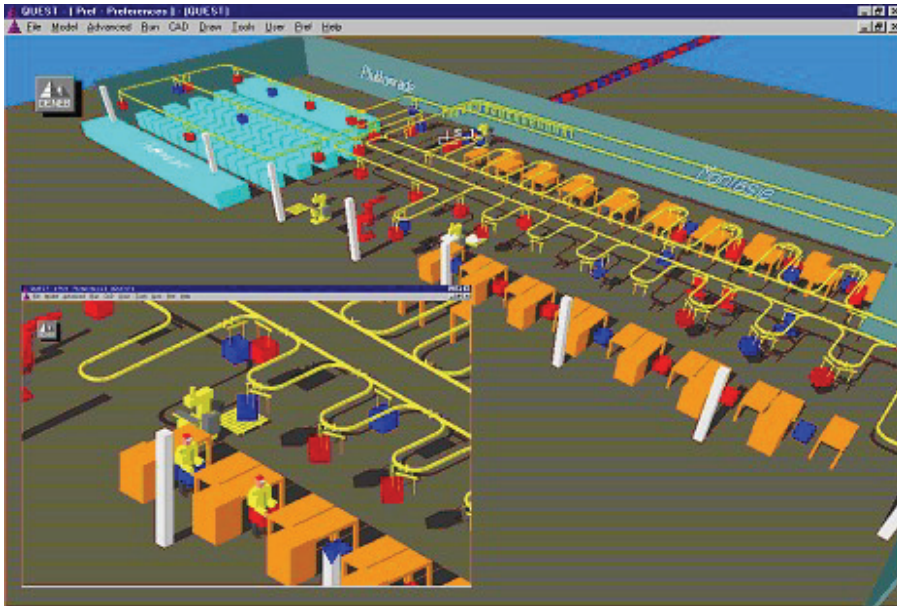


Figure 9-8: Discrete-event simulation software allows developing animated 3-dimensional visualizations of production plants. Here the software system *Quest* was used.

The development of discrete-event simulation models is rather time-consuming and requires training and expertise. Some statistical knowledge is also required, but it lies within the grasp of non-mathematicians. Their use is also relatively time-consuming because often, one has to test many scenarios before a satisfactory solution is found. Moreover, each scenario must be run several times (replicated runs) in order to achieve a desired level of statistical significance.

The models are therefore usually developed and used by company-external, specialized simulation experts. The decision-makers suggest various scenarios to these experts, who then carry out the necessary simulation runs and report results back to the decision-makers. This somewhat complicates the use of these models for decision support. If the decision-makers have some basic discrete-event simulation knowledge, they can carry out certain types of model experiments themselves. For the software system *Quest*, for example, low-price licences can be purchased with restricted functionality. While the model structure cannot be manipulated with such licences, they allow non-experts to modify parameter values and thus to carry out simple experiments themselves.

For references to application examples in a variety of industries, see Appendices A and B. Textbooks in discrete-event simulation normally discuss its use for production system analysis, for example Banks et al. (2005), Robinson (2004) and Brooks et al. (Brooks et al. 2001).

9.10 OR for inventory management

This section is concerned with the use of OR techniques to support tactical and operational decisions related to controlling inventories of raw materials, components and finished goods. Such decisions concern the selection of suitable inventory management policies, setting

appropriate parameter values and determining actual replenishment times and quantities. First, the different techniques' applicability is discussed, with focus on the detailed problem situations in which they can be beneficial. Thereafter, the way they support decision-making is briefly described.

Note that several other decision types concern inventory-related issues. Plant location and distribution system design determines the warehouse structure that satisfies customer service requirements at lowest total cost. Aggregate production and capacity planning helps decide how much inventory to build ahead of peak selling periods. Production plant design involves locating and sizing buffers between production steps within a plant, and production rules/policies determine work-in-process levels and production lot sizes. The applicability of OR techniques for these decision types is treated in other sections in the present guidelines.

9.10.1 Applicability of OR techniques

OR techniques have successfully supported several key issues in inventory management. *Lot sizing* concerns the size of orders made to external suppliers or company-internal production resources. Since lot sizes are inversely proportional to replenishment frequencies, once either of these parameters is determined, the other one is as well. Lot size decisions are often supported by **single-stage inventory theory** (advanced application example: Katok et al. 2001a). The term 'single-stage' is used to indicate that lot sizes are not coordinated across several supply chain echelons. The most frequently used model is the economic order quantity (EOQ) formula (see Subsection 5.3.4 for details), which balances reorder and inventory carrying costs. It is appropriate when the product can be reordered repeatedly. If the product can only be ordered once, such as clothes in the beginning of the season, the 'Newsvendor formula' is more appropriate; see Wild (2002) and Silver et al. (1998) for details. The literature also suggests numerous other models, each for somewhat other problem situation characteristics, but in the researcher's experience, their use in practice is more infrequent.

Some additional guidance on when to use the EOQ model can be found in the literature. Hopp and Spearman (2001) remark that it is most appropriate to determine purchasing quantities from external suppliers because order costs can be clearly interpreted as the cost of placing a purchase order and estimated quite precisely. It must be emphasized, however, that replenishment quantities from suppliers should also be affected by transportation costs and the suppliers' production capacities and priorities, if they are to be effective for the supply chain as a whole. The use of vendor-managed inventories can provide an incentive to include such factors. For lot sizing in production, EOQs tend to be too large (Wild 2002). This issue is further discussed in subsection 9.12.1. Silver et al. (1998) emphasize that the EOQ is based on the assumption that demand is constant over time, and that it therefore should only be used when demand does not vary too much. They propose the following rule: If the variability coefficient

$$\frac{\text{Variance of demand per period}}{\text{Square of average demand per period}}$$

is less than 0.2, then the EOQ formula constitutes a suitable approximation. They present several alternative models for situations when the variability coefficient is larger or equal to 0.2.

In the face of uncertain demand, *safety stock* decisions determine how much stock to keep of each finished product so that a required customer service level in terms of product availability

is achieved. For raw materials and components, safety stock levels are determined to guarantee a desired level of material availability for subsequent processing stages. Based on the safety stock levels, reorder points are determined.

If a single inventory (one buffer or warehouse) is considered, **single-stage inventory theory** is again employed (application example: Kapuscinski et al. 2004). In particular, the safety stock formula presented in Subsection 5.3.4 is frequently used. Note, however, that this formula assumes demand during replenishment lead time to be normally distributed. This is normally a reasonable assumption when demand is large and regular. For slow-moving items, the Poisson distribution might be more appropriate. See Wild (2002) for further details.

Among the weaknesses of such formulae is that they do not coordinate a product's safety stock with those of other products (such as substitutes). Another, possibly more severe limitation is that safety stock decisions are not coordinated with inventories at other locations or supply chain echelons. If the logistics system considered consists of stock locations at several vertical echelons, such as before packing, after packing, at distribution centres and at retail outlets, determining safety stock requirements independently at each echelon often leads to unnecessarily high safety stock levels. In such uncoordinated situations, upstream stock locations typically carry too much safety stock.

This can be avoided by using **multi-echelon inventory theory**. Multi-echelon inventory theory helps determine at which stage(s) in the supply chain to keep safety stock, and how much to keep. It takes a holistic supply chain perspective and calculates safety stocks at each stage so that desired service levels (in terms of product availability) to external customers are achieved with as little inventory as possible in the supply chain in total. The technique thereby implicitly also addresses questions related to postponement/speculation, T-points and customer order decoupling points. For application examples, see Troyer et al. (2005), Billington et al. (2004), Lin et al. (2000) and Lee and Billington (1995).

Multi-echelon inventory theory normally requires *decentralized*, but *coordinated* organization in the supply chain. That is, inventories are managed locally with simple control policies, except that safety stock levels are determined centrally and communicated to the different inventory locations. The implementation of multi-echelon inventory theory is somewhat time- and resource-consuming. It will therefore mainly be worthwhile when considerable capital is tied up as inventory, typically because of

- a large number of different stock keeping units
- high-value products such as computers and electronic equipment
- safety stocks held at numerous sites and production stages
- long lead times in production and transportation between locations

To the researcher's knowledge, multi-echelon inventory theory is in Europe so far only used by very large companies. Nevertheless, simple multi-echelon approaches, such as the echelon inventory policy proposed by Simchi-Levi et al. (2008), should not be too difficult to implement in practice, and be beneficial also to smaller companies. The researcher expects an increasing number of such implementations in the near future.

In the *Interfaces* papers surveyed, there are fifteen descriptions of how inventory theory supports inventory management. Eight describe the use of multi-echelon inventory models,

which confirms the applicability of such models in practice. The remaining seven papers present the use of single-location inventory models. It is well-known that such models are implemented and used daily in many standard inventory management systems. Single-location inventory models are certainly underrepresented in the survey sample, simply because they are only in exceptional situations considered as novel or sophisticated enough to be worth a publication.

Models from inventory theory, such as those mentioned above, allow on-line and automatic, periodical calculation of reorder quantities and safety stocks for typically a large number of different stock-keeping units. For more detailed, tactical analysis of various inventory policies and parameters (fixed order quantity vs. fixed order period, postponement vs. speculation, risk pooling etc.), **discrete-event simulation** can sometimes be useful (application example: Dalal et al. 2003). This technique typically requires fewer assumptions and can include many more details than inventory theory. However, both surveys carried out in this thesis suggest that discrete-event simulation is somewhat less frequently used to support inventory management. It seems that companies rely on inventory theory and only occasionally use discrete-event simulation for more detailed analysis. The discussion in Section 7.4.3 also suggests that developing discrete-event simulation models of inventories at several supply chain locations (supply chain simulations) can be rather challenging.

Finally, note (from appendix A) that most *Interfaces* papers on inventory management were published in recent years. This reflects recent years' focus on inventory reductions in general, and from a supply chain wide perspective in particular (Chopra and Meindl 2007, Christopher 2005). It implies an increasing number of opportunities to apply OR models in inventory management.

Table 9-8: The purposes of OR techniques used to support inventory management

Technique	Purpose
Single-stage inventory theory for lot sizing	Quick, on-line calculation of reorder quantities for typically a large number of different raw materials, components and finished products. No coordination across different items or supply chain echelons.
Single-stage inventory theory for safety stock calculations	Quick, on-line and periodical calculation of safety stock requirements for typically a large number of different raw materials, components and finished products experiencing uncertain demand. No coordination across different items or supply chain echelons.
Multi-echelon inventory theory	Determine at which stages in the supply chain to keep safety stock (tactical). Quick, on-line and periodical calculation of required safety stock levels for each item and at each supply chain echelon (operational). Coordination across echelons.
Discrete-event simulation	Detailed, tactical analysis of different inventory policies and parameter values, such as fixed order quantity vs. fixed order period, postponement vs. speculation, risk pooling etc.

Table 9-8 summarizes the purposes of the discussed OR techniques. The remainder of this section describes the uses of inventory theory in more detail. The use of discrete-event simulation models (of supply chains) was described in Subsection 9.8.3.

9.10.2 Single-stage inventory theory for lot sizing

This subsection briefly describes how models from single-stage inventory theory are used to support lot size decisions. Focus is on issues that are specific for this type of application. For a more general description and characterization of inventory theory, including the EOQ formula, see Subsection 5.3.4 and Section 5.4.

As explained, such models are often used for quick, on-line calculation of reorder quantities for raw materials, components and finished products (even though such quantities should also be coordinated with the suppliers' production). As such, they also crucially affect transportation quantities from suppliers. At a more strategic level, the models help estimate cycle stock requirements for different plant/warehouse network configurations.

The EOQ formula is, in the researcher's experience, the most frequently used model for lot sizing in practice. The input data required are average demand per period, inventory carrying costs per unit per period and the costs of placing a replenishment order. It calculates the reorder quantity that provides the lowest total costs, i.e. the best trade-off between these two cost types (Figure 9-9). The EOQ formula makes a lot of simplifying assumptions, such as known demand that is constant over time, unlimited material/product availability and immediate delivery (Hopp and Spearman 2001). Moreover, it considers inventory carrying costs and reorder costs as known and fixed even though they can be difficult to estimate in practice. Despite these unrealistic assumptions, the EOQ formula can often provide useful insights into lot sizing issues because it is simple, fast and requires little input data. It is also rather robust, in the sense that moderate changes in the input data have limited effect on the result. This can be seen in the total cost curve in Figure 9-9, which is typically very flat around the minimum (where the EOQ lies). As a consequence, some uncertainty in input data does not seriously affect the lot sizes.

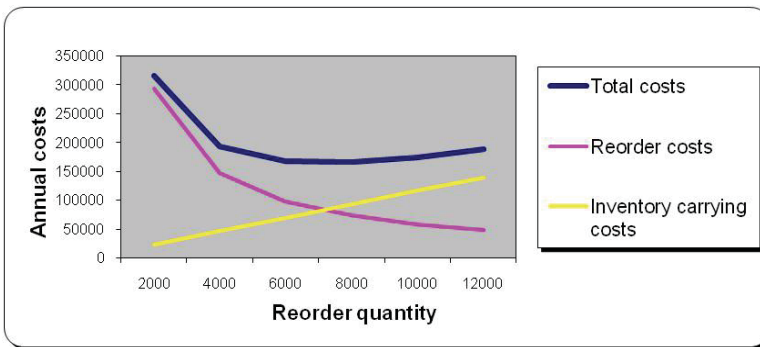


Figure 9-9: The EOQ finds the best trade-off between inventory carrying costs and reorder costs.

EOQ formulae are implemented in many corporate planning systems, especially replenishment systems, purchasing systems and inventory management systems. They can support purchasing managers in their daily planning of reorder quantities, often for thousands of different stock keeping units. Typically, the planning systems automatically make purchasing order suggestions based on EOQ calculations. The managers verify these suggestions and either confirm them or make necessary adjustments based on market knowledge, supplier offers etc. For more tactical/strategic analysis of lot sizes and cycle stocks, EOQs are also calculated off-line, for example in spreadsheets.

While the EOQ is most popular in practice, the use of other inventory-theoretic models is actually in many situations more appropriate. As explained, the so-called Newsvendor formula addresses situations where products only can be ordered once. It calculates the order quantity that provides the best trade-off between the risk of buying too much and the risk of buying too little. Other models address the trade-off between inventory and transportation costs. There are also numerous extensions of the EOQ formula, relaxing some of its assumptions. In general, the development of such more advanced models can be somewhat more time- and resource-consuming and require somewhat more advanced mathematical knowledge. Once they are implemented, however, they are usually fast and simple to use.

Good treatments of single-stage inventory theory for lot sizing can be found in textbooks on inventory management, such as Silver et al. (1998) and on supply chain management, such as Chopra and Meindl (2010) and Simchi-Levi et al. (2008). For a somewhat more mathematical, but still application-oriented text, see Hopp and Spearman (2001). For a practical, critical perspective on EOQ, see Wild (2002).

9.10.3 Single-stage inventory theory for safety stock decisions

This subsection briefly describes how models from single-stage inventory theory are used to support safety stock decisions. Focus is on issues that are specific for this type of application. For a more general description and characterization of inventory theory, including the basic safety stock formula, see Subsection 5.3.4 and Section 5.4.

As explained, such models help decide how much safety stock to keep of material/products experiencing uncertain demand. Each product and inventory location is treated separately. Typical input data include demand and lead times, expressed by means of probability distributions such as the normal distribution. The desired level of material/product availability is also specified. Based on these input data, the models calculate safety stock requirements such that the desired level of material/product availability is achieved with as little inventory as possible.

Specifying the desired level of product availability can be challenging. It requires that the company has agreed on a customer service strategy, typically distinguishing between different customer types, markets and product segments. One should also be aware that what counts for the external customer is delivery precision, not product availability. A high level of the latter does, however, not automatically imply a high level of the former.

The basic safety stock formula assumes demand to be normally distributed, even though this is not always a reasonable assumption in practice. Nevertheless, it is a very popular formula because it is simple, fast and requires little input data. It can calculate safety stocks automatically within seconds for hundreds or thousands of different stock keeping units. It is also robust, in the sense that it indicates somewhat more safety stock than what would strictly be required. There are also more advanced models, sometimes solved by means of algorithms rather than formulae, but in the researcher's experience, their use in practice is more infrequent. Their development is typically more time-consuming and requires more advanced mathematical knowledge; once they are implemented, however, they usually provide fast answers.

Basic formulae are implemented and used for operational purposes in many corporate planning systems, especially replenishment systems, purchasing systems and inventory

management systems. Typically, such systems quickly and periodically calculate reorder points for numerous different stock keeping units by means of the following formula:

$$\text{Reorder point} = (\text{Forecasted demand during replenishment lead time}) + (\text{safety stock})$$

Data transfer, especially updated forecasts, is on-line and automatic. Whenever the inventory level of an item falls below its reorder point, the system generates a replenishment order.

Best practice in inventory management differentiates between A, B and C-products and uses the systems' calculations differently (Table 9-9; based on Wild 2002). When products are sorted according sales value, the 5% of the products with highest sales value are classified as A-products. They often constitute up to 80% of total sales. B-products stand for then next 15% of the product spectre, often corresponding to approximately 15% of total sales. The remaining 80% of the product spectre, finally, are classified as C-products; they typically make a limited contribution to sales, such as 5% only.

Table 9-9: Inventory theory should be used differently for different product types (based on Wild 2002).

Product type	% of sales value	% of variants	Method of use
A	80	5	Careful check of automatically generated forecasts and replenishment orders to account for market knowledge, campaigns etc.
B	15	15	The system's automatic calculations are trusted more directly. Manual follow-up of 'flagged' products, with adjustment of parameter values and forecasts.
C	5	80	If C-products are to be kept in stock at all, parameters are chosen so that enough stock is kept to cover at least one complete customer order. The system's automatic calculations and replenishment proposals are then followed.

A-products are so important and few that planners should carefully check and adjust the replenishment orders generated by the system. Knowledge about market behaviour, campaigns etc. is usually available for these products and should be incorporated in the final replenishment decisions. For B-products, planners should to a large extent rely on the system's calculations; personal follow-up would be ineffective for such a large number of stock keeping units and lead to limited improvements. However, the system should 'flag' B-products demonstrating particularly low forecasting accuracy; for such products, the planners need to perform a check of the forecasting parameters in the system. Even less attention can be paid to C-products. Such products have typically very irregular demand, with many 0-demand periods. In such situations, the safety stock levels suggested by the model risk being too low to cover any complete order (because demand during lead time is normally assumed to be normally distributed). If such products are to be kept in stock at all, system parameters should be chosen such that at least one complete order can be covered (i.e. somewhat higher safety stock levels). Order quantities may also be relatively high. This way, work is minimized and a certain service level assured.

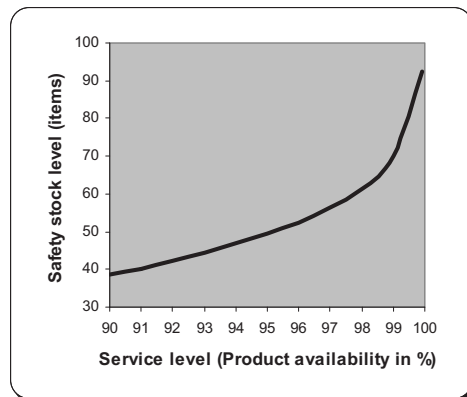


Figure 9-10: This graph shows how safety stock requirements depend on the desired level of product availability.

Safety stock models are also used in more tactical, irregular analyses. In this case, analysts use them off-line, typically implemented in spreadsheets. For example, if there is doubt about the desired level of material/product availability, different levels' effects on safety stock requirements can be assessed (Figure 9-10). Within the context of distribution system design, they can be used to estimate inventory investments for different alternatives, such as centralized vs. decentralized warehouse structures. Within the context of transportation management, they can help assess the effect of different transportation modes and lead times on safety stock requirements.

Good treatments of single-stage safety stock models can be found in textbooks on inventory management, such as Silver et al. (1998) and on supply chain management, such as Chopra and Meindl (2010) Simchi-Levi et al. (2008) and. For a somewhat more mathematical, but still application-oriented text, see Hopp and Spearman (2001). For an easy-to-read, practical treatment of the basics, see Wild (2002).

9.10.4 Multi-echelon inventory theory for safety stock decisions

This subsection briefly describes how multi-echelon inventory theory is used to support safety stock decisions. Focus is on issues that are specific for this type of application. For a general description and characterization of inventory theory, see Subsection 5.3.4 and Section 5.4.

As explained, the technique calculates safety stock requirements at the different locations in multi-echelon supply chains, such as the one in Figure 9-11, such that a desired level of product availability to external customers is achieved at lowest total inventory costs. While very simple models are based on formulae, the majority uses somewhat more advanced mathematical algorithms to calculate the required safety stocks.

As in inventory theory more generally, input data needs are relatively low. For each location, external customer demand is specified by means of probability distributions, usually normal distributions. Service level requirements (in terms of product availability) also need to be specified per location. Input data also include material flows, bills-of-materials, lead times (again expressed by probability distributions), and different cost types, such as inventory carrying costs, processing costs and costs of purchased components.

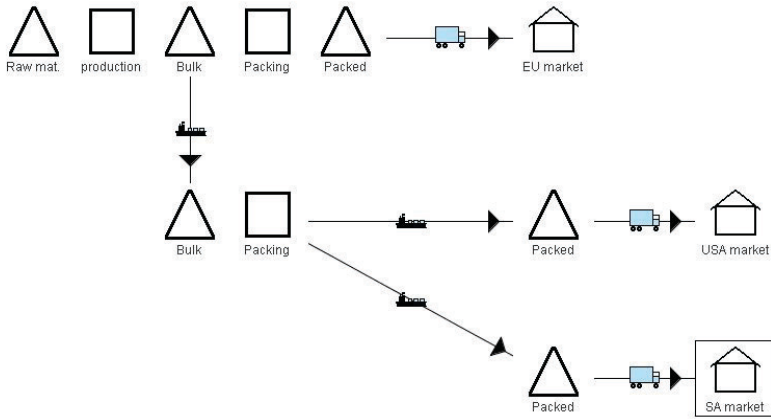


Figure 9-11: Simple example of a multi-echelon supply chain

Several remarks related to this input data should be made. Specifying the desired levels of product availability can be challenging, even more challenging than if each location calculates safety stock requirements separately. It requires that the company has agreed on a *supply chain wide* customer service strategy, typically distinguishing between different customer types, markets and product segments. If such a strategy is not available, it can be difficult to feed the models with the required data. As for single-stage models, one should also be aware that what counts for the external customer is delivery precision, not product availability. A high level of the latter does, however, not automatically imply a high level of the former.

Note also that input data usually assumes demand during replenishment lead time to be normally distributed. For slow-moving items, this assumption is violated and leads to safety stocks that are too low to cover any complete order. Finally, the models require cost estimates that can be difficult to make in practice. As a consequence of such challenges, it is important to critically assess the accuracy of a model before it is used for decision-making.

A number of commercial multi-echelon inventory management systems have recently appeared, each using its own models. Examples include *PowerChain Inventory* by *Optiant* and *MIPO* by *SmartOps*. Such systems have had a certain success, especially in very large companies. Figure 9-12 shows a screenshot from *PowerChain Inventory*. The screenshot visualizes the different supply chain stages and material flows; it also indicates, with small red triangles, where to keep safety stock.

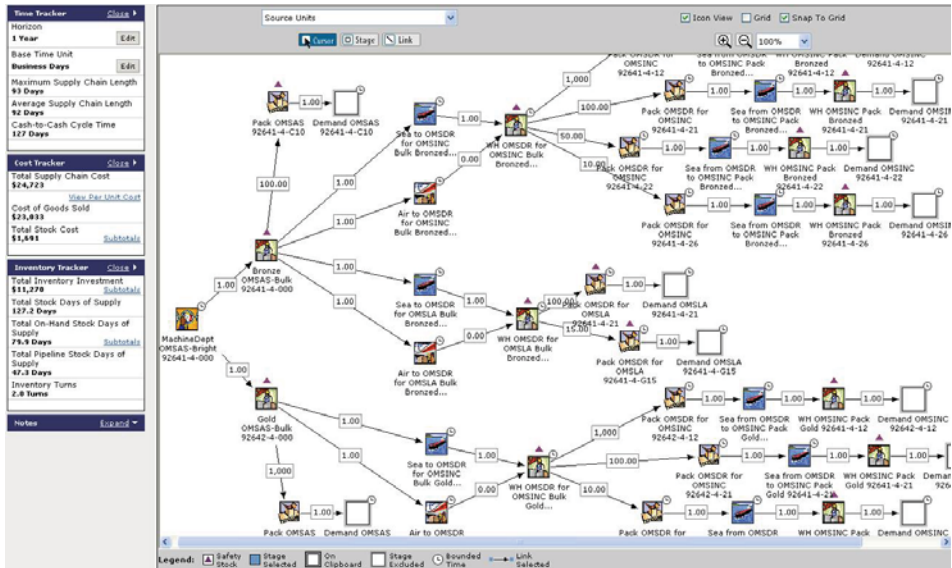


Figure 9-12: A screenshot from *Optiant's* multi-echelon inventory system *PowerChain Inventory*.

Such systems can be used in different ways. At a very operational level, they can automatically and periodically calculate the levels of safety stock required at all locations. In this type of application, they are typically closely integrated with other corporate data systems, with automatic data transfer in both directions. Updated demand information is fed into the multi-echelon system; safety stock requirements are returned and used to generate replenishment orders. While orders generated by single-stage models could be modified based on planners' experience and market knowledge, those generated by multi-echelon models need to be strictly adhered. That is, planners are required to respect the timings and quantities calculated by the system, even though they can seem flawed or irrational from their local perspective. Otherwise, the benefits from coordinating safety stock decisions across locations will not be achieved.

Multi-echelon systems can also be used for more tactical/strategic analysis. They may be used more sporadically, for example quarterly, to determine at which stages in the supply chain to keep stock and how much. They can also help assess the effect of different plant/warehouse network structures, transportation modes (lead times), levels of demand fluctuations etc. on safety stock requirements. For this type of analyses, the systems are often used off-line by analysts. Decision-makers are responsible for problem definition and data collection, analysts carry out the necessary model manipulations and report findings. In such tactical/strategic situations, the final decisions, will, however, often not be based solely on model results.

Since recent software systems have become more and more user-friendly, the time required for model development is typically in the order of weeks only. While the models are usually developed and implemented by dedicated consultants, advanced mathematical expertise is normally required neither for development/implementation nor for their use. So it should be possible to perform these tasks company-internally without excessive training periods.

The following literature is recommended for further reading. Lee (2003) has written an easy-to-read white paper. Simchi-Levi et al. (2008) propose the ‘echelon inventory policy’ as a simple way to achieve coordinated inventory management in supply chains. For more advanced mathematical reading, see Swaminathan and Tayur (2003) or Graves and Willems (2003).

9.11 OR for aggregate production and capacity planning

This section is concerned with the use of OR techniques to support tactical production and capacity planning. Mainly, deterministic optimization is used. Its applicability is discussed first, with focus on the detailed problem situations in which it can be beneficial. Thereafter, the way it works is briefly described.

9.11.1 Applicability of OR techniques

Deterministic optimization, more precisely linear/mixed-integer programming, helps decide how much of each product group to produce, assemble, package and store in each period. That is, it calculates cost-effective ways to meet forecast demand by adjusting regular and overtime production rates, inventory levels, labour levels as well as subcontracting and backordering rates. It determines necessary capacity expansions and the build-up of seasonal stock. The scope can be a single production plant or a network of several plants (and warehouses). If several plants are considered, aggregate transportation quantities from suppliers to plants, between plants and from plants to customers are also determined for each period. The planning horizon is typically 6-18 months, the time periods weeks or months. The result is a plan that provides input for detailed, short-term production planning/scheduling.

It seems that deterministic optimization enjoys particularly high applicability exactly in multi-plant situations, where a company wishes to *centrally coordinate* aggregate plans for several production plants/warehouses. The *Interfaces* survey revealed nine such applications. Aggregate production planning coordinating several plants is sometimes called *supply chain master planning*, especially if it is done using deterministic optimization (for example by Stadtler and Kilger 2005). Note that it assumes that production and transportation quantities are independent (make-to-stock production) and that production and transportation can take place in different periods (Rohde and Wagner 2005). Its use implies a rather high degree of centralization.

For single plants, there seem to be fewer successful applications; the *Interfaces* survey only identified Gazmuri and Maturana (2001) and Taube-Netto (1996). For this scope, the survey therefore supports repeated claims that aggregate planning theory is of limited applicability in practice (Buxey 2005, 1995, Nam and Logendran 1992). It seems that there are certain practical problems related to the implementation of theory. As an interesting path of further research, the reasons can be investigated and more suitable approaches developed.

Here, a number of problem situation characteristics are tentatively collected that seem to favour the deterministic optimization approach to aggregate planning. In order to balance supply and demand correctly, forecasts should be relatively good and production processes have limited output variance when aggregated to an entire period (Rohde and Wagner 2005). Otherwise, it will be difficult to determine the capacity levels needed. Deterministic optimization is often employed by companies whose products experience predictable seasonal demand variations (Buxey 2005). This is because the build-up of seasonal stock is a well-addressed issue by the models. It requires, however, that intermediates and finished products

can be stored for several periods (weeks/months). If products are perishable, such as fresh food, it is not possible to use inventory to cope with seasonal variations.

Although not directly related to the applicability of OR, a comment concerning model size is worthwhile here. The size of the supply chain master planning models described in *Interfaces* varies considerably: Schuster and Allen (1998) describe a simple spreadsheet application with 324 decision variables and 361 constraints. In contrast, the chick planning module in Taube-Netto (1996) had 130000 variables and 35000 constraints. Some of this difference may be attributable to varying complexity of the real system, but much is likely to be due to unequal levels of aggregation and levels of detail. Thus, very different degrees of model simplification have been used for supply chain master planning in practice.

Table 9-10: The main OR technique used to support aggregate production and capacity planning is deterministic optimization.

Technique	Purpose
Deterministic optimization	Centrally determine how much to produce, assemble, package and store in each period (often month) at each plant and warehouse, typically in supply chains experiencing predictable seasonal demand.

Table 9-10 summarizes the purpose of deterministic optimization in the context of aggregate production and capacity planning. The remainder of this section provides some further details about its use. Focus is on issues that are specific for this type of application. For a general description and characterization of deterministic optimization, see Subsection 5.3.1 and Section 5.4.

9.11.2 Deterministic optimization for aggregate production and capacity planning

Typical input data required for this type of OR application include:

- Aggregate demand forecasts per plant, product group and time period
- Capacities of resource groups, such as labour, machines, buffers/warehouses and transportation equipment
- Minimum inventory levels (required safety stocks) and actual inventory levels
- Inventory costs, regular/overtime production costs, transportation costs

All these data are assumed to be known with certainty and expressed by fixed numbers. The relationships between the data are usually assumed to be linear; in particular, costs and capacity requirements are assumed to be linear in product volumes. Lead times are not considered in detail, but approximated by normally one time period (month).

Based on these input data and basic assumptions, the models calculate plans that minimize total costs, i.e. they find the cost-minimizing trade-off between the different cost types while respecting constraints related to demand, capacities, inventory levels etc. The resulting plans can be illustrated by means of graphs such as the one in Figure 9-13. Such graphs illustrate well how inventory is built up ahead of peak selling periods. In order to account for uncertainty in input data, the models can specify how much the input data can change before

the solution changes (sensitivity analysis). Various scenarios can be tested by changing input parameter values such as demand, costs and capacities (scenario analysis).

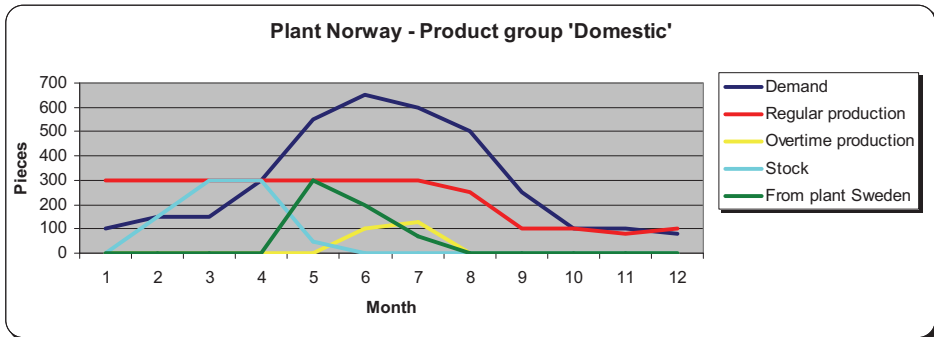


Figure 9-13: Aggregate production and capacity plans show how much to produce, store, and deliver in each time period.

Since aggregate production/capacity planning is carried out periodically, the models are normally used directly by planners. Typically, the following steps are performed each time a new plan is required:

1. Gather relevant data.
2. Use the OR model to calculate a tentative plan.
3. Analyse the plan, if necessary make some additional model runs with modified input data. Make manual adjustments.
4. Release plan, gather feedback from lower planning levels, adjust plan, possibly again after some additional model runs.

Thus, the models help planners learn more about the situation and alternative options. Qualitative considerations, experience, tacit knowledge and other factors will normally also affect the final plan.

The type of software system required depends on the size and complexity of the particular model. Simple models can be solved with solvers implemented in spreadsheet software. More frequently, however, so-called general-purpose optimization packages are used. Advanced planning and scheduling (APS) systems provide standardized software modules for aggregate production and capacity planning, but their success has been limited because in most cases, highly customized solutions are required. See page 71 for further details on APS systems.

Since customized solutions are needed, the *development and implementation* of such models is rather time/resource-consuming. There is a need for advanced knowledge and experience in OR and database management. Since aggregate production planning must be carried out periodically, user-friendly interfaces should be made available so that planners can use the models themselves. This reduces the need for experts or complicated model manipulations once they are implemented. Time and resource requirements for model *use* are then quite low. Probably one of the main challenges is to obtain correct and updated data.

For numerous application examples, see Appendix A. For further literature, see Chopra and Meindl (2007) or Rohde and Wagner (2005).

9.12 OR for the determination of production rules/policies

This section is concerned with the use of OR techniques to support the evaluation and selection of production rules and policies (tactical). Examples include determining work-in-process levels, priority rules, routing policies, tactical lot sizing, cyclic scheduling, KANBAN card quantities as well as procedures to be used for short-term production planning/scheduling. First, the different techniques' applicability is discussed, with focus on the detailed problem situations in which they can be beneficial. Thereafter, the way they support decision-making is briefly described.

9.12.1 Applicability of OR techniques

The *Interfaces* survey confirms that, as for production plant design, the OR techniques frequently used to determine production rules/policies are **queuing theory** and **discrete-event simulation**. In addition, both the *Interfaces* survey, the *Winter Simulation Conference* survey and the survey carried out by the Simulation Study Group (1991) indicate that these two decision types are among the most important application areas of queuing theory and discrete-event simulation.

Discrete-event simulation and queuing theory models represent the inside of a production plant as a set of resources with material waiting in queues before these resources, being processed, and being moved to the next resource. If the buffer before a resource is empty, the resource is starved, if the buffer after is full, the resource is blocked. They are therefore particularly useful when the arrival of items before resources is irregular and leads to queues in the real system. They can be used to analyze and test a wide spectre of issues related to production rules and policies.

The characteristics of the problem situation determine which of these two techniques is most appropriate. If basic issues are to be studied for simple, serial production/assembly lines, for example work-in-process levels, queuing theory can be appropriate (application example: Srinivasan et al. 2003). The three applications of queuing theory identified in the *Interfaces* survey were all carried out in the transportation equipment industry.

If the production system is more complex and includes, for example, multiple products with different processing flows, splits and merges with different routing policies, carrier subsystems and closed-loop conveyances, then the flexibility of discrete-event simulation is often required in order to achieve a sufficiently accurate model (Alden et al. 2006). All sorts of production systems can be simulated, such as production/assembly lines, job shops, material handling systems, production cells and flexible manufacturing systems. As both this thesis' surveys show, the technique has been applied in a variety of industries (Appendix A and B). For an application example in the food industry, see the Gilde Norsk Kjøtt case in Section 8.3, where the simulation model was developed and updated in parallel with the physical extension of the plant. In general, discrete-event simulation is often used when a new production plant is designed, as well as diagnostically to test various improvement ideas in existing plants. Developing realistic models is easiest if the production system consists of stable processes.

'Spreadsheet' simulations and **factory physics principles** (see Hopp and Spearman 2001) are certainly also used to analyze production rules/policies, but their use is not normally

reported in research literature such as *Interfaces*. From reading the applications reported in *Interfaces*, it seems that, when advanced queuing or discrete-event simulation models were developed, the main purpose was often to support production plant design. A reasonable explanation is that it is easier to justify the development of advanced models for such important, strategic decisions than for tactical rules/policies. Once a model of the plant is available, however, it can be readily used to analyze the latter as well.

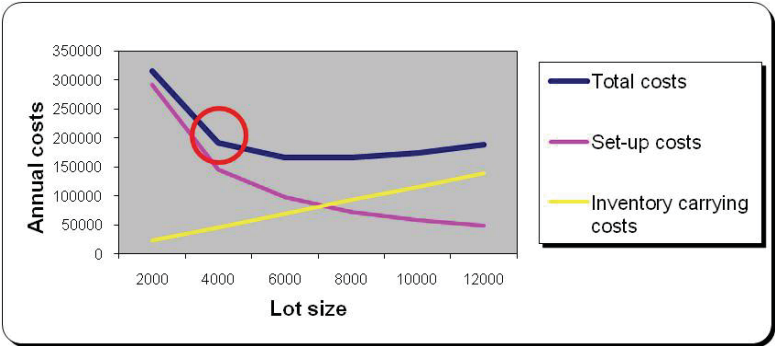


Figure 9-14: Production lot sizes should typically be placed at the very left end of the flat area of the total cost curve.

For the calculation of production lot sizes, corporate planning systems often use models from inventory theory, especially the economic order quantity (EOQ) model (see Subsection 5.3.4 for details). Such models aim to find lot sizes that minimize the sum of set-up and inventory carrying costs. While such an approach can seem plausible, just-in-time, lean and related production philosophies emphasize the use of lot sizes that are much smaller than EOQs. Among the reasons why EOQs tend to be too high is their ignorance of benefits from increased flexibility and smoother production with small lot sizes. An additional weakness of EOQs is that they do not take into account resource capacity restrictions or suggest lot sizes that lead to efficient capacity utilization. Moreover, set-up and inventory carrying costs are notoriously difficult to estimate.

EOQs should therefore be used with care in production. Wild (2002) suggests lot sizes to be in the order of 60% of EOQ. Similarly, lean theory recommends that lot sizes be at the very left end of the flat area of the total inventory plus set-up cost curve (www.strategos.inc/lean_lot_sizing.htm; see Figure 9-14). Such rules do, however, not normally apply to bottleneck resources, for which higher lot sizes should be chosen since time used for set-ups should be kept as low as possible.

Table 9-11: The purposes of OR techniques that can help determine production rules/policies

Technique	Purpose
Queuing theory	Determine work-in-process levels and related issues in simple, serial production/assembly lines; determine KANBAN card quantities
Discrete-event simulation	Determine work-in-process levels, routing policies, priority rules, cyclic schedules, KANBAN card quantities etc. in more complex production systems, with splits, merges, multiple products, complex priority rules, carrier subsystems etc.
'Spreadsheet' simulation, factory physics principles	Quick, rough calculations when there is no time or need for more detailed analysis. Also used in combination with more advanced techniques.

Table 9-11 summarizes the purposes of the discussed OR techniques. The use of queuing theory was described in more detail in Subsection 9.9.2, the use of discrete-event simulation in Subsection 9.9.3.

9.13 OR for transportation management

This section is concerned with the use of OR techniques to support manufacturing companies in managing transportation. Transportation management concerns tactical decisions (policies) and operational decisions (deployment) related to transportation between supply chain points, such as suppliers, plants, warehouses and customers. Typical decisions include frequencies and lot sizes, transportation mode and distribution path selection, vehicle packing and vehicle routing and scheduling. First, the different techniques' applicability is discussed, with focus on the detailed problem situations in which they can be beneficial. Thereafter, the way deterministic optimization supports vehicle routing and scheduling is briefly described.

Note that several other decision types concern transportation-related issues. In plant location and physical distribution system design, plants/warehouses are strategically allocated to customer areas, determining overall transportation quantities between plants/warehouses and customers. In aggregate production and capacity planning, aggregate (for example monthly) transport quantities from suppliers and between plants/warehouses are determined. Internal transportation is addressed by production plant design and production rules/policies. The applicability of OR to support these decision types is discussed in other sections of the present guidelines.

9.13.1 Applicability of OR techniques

In order to discuss the use and applicability of OR techniques in transportation management, one should be aware of the different parties involved in transportation, each having its own perspective and goals. The *recipient* (customer) places an order and thereby triggers a transportation need; the *shipper* requires the movement of the order from its own facility to the recipient's location; the *carrier*, finally, performs the physical transportation of the order (Figure 9-15). The goal of the recipient is often to balance inventory and reorder costs. The shipper tries to use transportation in a way that minimizes total costs (transportation, inventory, sourcing, fixed plant costs etc.) while providing an appropriate level of responsiveness to the customer. The carrier, finally, makes strategic/tactical investment decisions regarding the transportation equipment and makes operational decisions that maximize the return from these assets (Chopra and Meindl 2010).

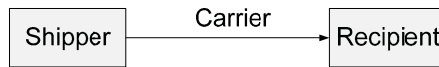


Figure 9-15: The different parties involved in transportation

In the context of transportation from suppliers (procurement), the manufacturer has the role of the recipient. In order to balance inventory and reorder costs, the manufacturer often uses **inventory-theoretic models** to determine the size of replenishment orders, such as the economic order quantity (EOQ; see Subsection 5.3.4 for details). Orders sizes from distribution centres to company-internal production plants are often calculated similarly. This, however, takes a local recipient perspective. Inventory theory can also be used to address the trade-offs between inventory and transportation costs, which would often be more relevant. Moreover, production capacities and priorities (of suppliers or own plants) should also be considered, if solutions are to be effective for the supply chain as a whole. The use of vendor-managed inventories can provide an incentive to include such factors when deciding on transportation quantities. Once shipment sizes are decided, the frequency of transports is determined as well (frequency = demand/size).

The survey of *Interfaces* does not bear witness to the use of inventory-theoretic models for transportation management (see Table 7-2). As explained before, this is probably because they are not normally considered as novel or sophisticated enough to be worth a publication. It may also reflect that such models are usually primarily associated with inventory management, even though they affect transportation as well.

When a manufacturing company owns several stages in the supply chain, it takes the role of both shipper and recipient. In such situations, the company may wish a detailed, tactical study of different transportation policies, such as modes, frequencies, timing, less-than-truckload vs. full-truckload, cross-docking etc. **Discrete-event simulation** allows estimating the effect of such policies on performance measures and on other supply chain functions. It must be noted, however, that this type of analysis normally requires a considerable amount of time and resources if it is to provide useful decision support (see Subsection 7.4.3). This thesis' surveys only identified one paper describing the use of discrete-event simulation for transportation management (Dalal et al. 2003). In practice, rough approximations in '**spreadsheet simulations**' seem to be more common. To assess the impact of different transportation modes and lead times on safety stock requirements, **inventory theory** can again be used.

Within the context of final distribution from a given source location to customer locations, an important task is vehicle routing and scheduling. It is concerned with optimal utilization of transportation equipment and drivers while meeting service requirements (Bowersox et al. 2002). Typical decisions include:

- Which type of vehicle should be used for which routes, customer types and orders?
- Which orders should be delivered by which specific vehicle?
- What is the best delivery route/sequence?
- What are the best delivery schedule and the resulting delivery time windows?

Vehicle packing, i.e. planning how to pack the vehicle efficiently, is a related issue that needs to be synchronised with routing and scheduling (Chopra and Meindl 2010). All these issues can be tactical, for example to determine fixed routes, or operational, for short-term resource allocation on a daily/weekly basis.

Vehicle routing and scheduling is an important application area of OR. The main OR technique used is **deterministic optimization**. The literature contains a large body of such models and solution algorithms, and also in practice, the technique has been applied frequently. According to Chopra and Meindl (2010), the use of software to determine transportation routes has been the most common IT application in transportation. Toth and Vigo (2002) and Bowersox et al. (2002) also emphasize the large number of real-world applications, which generally lead to transportation cost savings from 5% to 20%. Transportation problems are highly structured, making them amendable to the use of deterministic optimization techniques (Barnhart and Laporte 2007). The software industry offers dozens of packages for the solution of vehicle routing and scheduling problems based on deterministic optimization.

The *Interfaces* survey, whose scope was restricted to manufacturing companies, only identified five such applications. This low number reflects that today, manufacturers usually outsource physical transportation to logistics service providers. Thus, in the context of final distribution, the manufacturer has the role of the shipper and leaves the role of the carrier to specialized transportation firms. Most vehicle routing and scheduling applications are carried out by logistics service providers, who typically consolidate shipments from several clients. From a manufacturing logistics perspective, vehicle routing and scheduling has therefore a somewhat more limited importance (Fleischmann 2005).

For some manufacturers, however, transportation is of such a strategic importance that they choose to take on the role of the carrier. They manage the transportation fleet themselves and possibly even own it. In such situations, the manufacturer is likely to benefit from optimization (Fleischmann 2005). Based on a closer study of the five *Interfaces* applications, as well as on experience from the Norwegian industry, the researcher conjectures two typical situations (and hybrids of them) in which manufacturers choose to carry out vehicle routing and scheduling themselves and often use OR for support:

1. Distribution of large amounts of bulk, such as slurry, cement and petroleum products, to an often global customer base by intermodal means such as boat and truck. Production is often continuous and coordination with transportation and inventory management important. High delivery precision is crucial because stock-outs at the customers can have severe consequences. Transportation costs typically stand for a large part of the total product costs, and the OR models typically focus on total cost minimization. Owning the transportation fleet in such situations, where shipment sizes are large and responsiveness is important, is generally a good solution (Chopra and Meindl 2010). The applications described Dauzère-Pérès et al. (2007) and Bausch et al. (1995) provide examples of this type.
2. Local distribution of perishable goods in partial loads, such as food, beverages or newspapers, to a dense customer base. Chopra and Meindl (2010) explain that when a firm serves a high density of customers close to the distribution centre, using its own fleet of trucks is often best because it makes good use of the vehicles. Moreover, due to the products' limited shelf lives, manufacturers are particularly concerned with timely and effective delivery to the consumer – which provides an incentive to keep

control. Adenzo-Dias et al. (1998) note that there have been many applications of routing and scheduling models in the food sector, ‘perhaps because of its special distribution characteristics’ (high-volume, low-margin products; limited shelf lives; many delivery locations). Golen et al. (2002) observe that the beverage, food and dairy industries have large volumes of sales so that the expenses associated with distribution activities are typically very large – a further incentive to keep control. The papers by Adenzo-Dias et al. (1998) and Martin (1998) both exemplify applications in this second typical situation.

Note that in both situations, there is often a need for specialized vehicles, which further increases the reasonableness of fleet ownership. Additional research is, however, necessary to validate the above conjectures.

It should also be mentioned that a certain type of deterministic optimization models, so-called inventory-routing models, can coordinate vehicle routing and scheduling with the management of inventories at origins and/or – in the case of vendor-management inventories – destinations. This has typically been done when large quantities of bulk, such as slurry or cement, are transported to customers by boat (Application example: Dauzère-Pérès et al. 2007).

An alternative to deterministic optimization for vehicle routing and scheduling is **interactive approaches**, which utilize a combination of ‘spreadsheet’ simulations and graphics capabilities to interact with decision-makers (Bowersox et al. 2002, Bott and Ballou 1986). The decision-makers specify alternative solutions, for which the data system calculates performance characteristics in terms of time and cost. The decision-makers then refine the strategy until no further improvement is likely. A drawback of this approach is that it depends on the skills of the decision-makers and does not suggest good solutions itself. This is particularly problematic if there are many alternative solutions. **Combinations** with deterministic optimization have proven very effective (Bowersox et al. 2002).

Bowersox et al. (2002) also explain that two important criteria when evaluating alternative decision support approaches are generalizability and accuracy. Generalizability is the ability to incorporate a particular situations’ particularities, such as multiple depots, time windows, vehicle capacities, legal driving times etc. Accuracy refers to the ability to closely approximate performance characteristics (validity) and provide results that are close to the ‘best’ (within the model’s assumptions).

Table 9-12: The purposes of OR techniques used to support transportation management

Technique	Purpose
Inventory theory for lot sizing	Calculate shipment sizes from suppliers and company-internal plants by balancing different cost types, such as inventory costs, reorder costs and transportation costs.
Discrete-event simulation	Estimate the effect of different transportation policies, such as modes, frequencies, timing, less-than-truckload vs. full-truckload, cross-docking etc. on costs and performance in the manufacturer's supply chain.
Inventory theory for safety stock calculations	Assess the impact of different transportation modes and lead times on safety stock requirements.
Deterministic optimization	Calculate tactical/operational vehicle routes and schedules for final distribution. Used by manufacturers that manage a transportation fleet themselves.
Interactive approaches	Estimate costs and times of alternative vehicle routes and schedules generated by planners, using graphics capabilities to interact with them. A simpler alternative to deterministic optimization for manufacturer with their own fleet.

Table 9-12 summarizes the purposes of the discussed OR techniques. The use of inventory theory for lot sizing was described in more detail in Subsection 9.10.2, the use of discrete-event simulation for supply chain analysis in Subsection 9.8.3, the use of inventory theory for safety stock calculations in Subsections 9.10.3 and 9.10.4. The remainder of this section concentrates on the use of deterministic optimization for vehicle routing and scheduling.

9.13.2 Deterministic optimization for vehicle routing and scheduling

This subsection briefly describes how deterministic optimization is used to support vehicle routing and scheduling. Focus is on issues that are specific for this type of application. For a more general description and characterization of deterministic optimization, see Subsections 5.3.1 and Section 5.4.

As explained, vehicle routing and scheduling models allocate orders to vehicles, find good delivery routes/sequences and develop detailed time schedules for deliveries. They are used operationally for short-term resource allocation, as well as tactically, for example to determine fixed routes. Input data requirements include (Chopra and Meindl 2010, Fleischmann 2005, Bowersox et al. 2002):

- Demand data. For operational support, precise data on shipments is used, such as size, origin, destination and desired delivery times (In vendor-managed inventory situations, such data may not be required as an input, but is determined by the model). For more tactical analyses, average demand per delivery destination is used, with a capacity allowance for extremely high demand periods.
- Information on the transportation network and infrastructure (distances, transit times, special constraints such as weight limits and tolls, etc.). Today, detailed geographical information systems (GIS) are normally used; they provide an extreme level of accuracy. The attributes and capabilities of such systems are constantly increasing and can also include real-time traffic information such as congestions. The more

traditional approach is to use straight line distances between supply chain points, which is cheaper but less accurate and cannot consider infrastructural constraints as well as GIS.

- Fleet information: The number and types of vehicles, their capacities and operating characteristics as well as driver constraints.
- Fixed and variable costs related to vehicles and drivers

Based on these input data, the models seek cost-minimizing transport solutions while meeting customer requirements (in terms of, for example, desired delivery time windows). Costs are minimized by means of effective vehicle and driver utilization and short routes, as well as – in inventory-routing models - by trading off inventory, transportation and production costs.

Since the models are deterministic, input data such as delivery quantities, travel times and costs are assumed to be known with certainty and expressed by fixed numbers. In order to account for operational uncertainties, some slack would typically be allowed, for example in transportation times and capacities. If time allows it, especially in tactical applications, the models can be run several times with different levels of demand, costs etc. (scenarios).

To calculate solutions, the models use heuristics or exact procedures. Heuristics quickly calculate good, but not necessarily optimal routes. Exact approaches often use integer programming (see Section 4.6) and calculate ‘optimal’ solutions (given the assumptions made in the model). The challenge with exact procedures is that even relatively simple models need a long time to be solved. While this issue is mitigated by on-going advances in OR and IT, many, if not most, models in use are based on heuristics. They yield solutions within minutes that are good enough in most operational situations. In more tactical applications, where time is less critical, they can be run somewhat longer, which allows identification of solutions that are even closer to the ‘optimum’.

The operational nature of vehicle routing and scheduling requires easy-to-use, interactive decision support software that can be used company-internally and does not require advanced OR knowledge. It is typically used daily in decision-making by staff responsible for transportation planning and scheduling. For example, they may be updated with order information once a day and calculate routes and schedules for the next day. A recent trend is that routes are calculated in real-time as new information on orders, fleet status, traffic etc. becomes available. Typically, the systems plot delivery origins, destinations and routes on a map. This provides an intuitive and straightforward understanding of the solutions suggested. Different symbols and colour codes are used to distinguish between different order states, vehicle types, activity types etc. Many systems also have drag-and-drop functionality that allows manual editing of routes. Gantt charts are used to show the scheduled tasks of each vehicle.

Companies who implement vehicle routing and scheduling software usually purchase a commercial software system. Such systems are so general that they normally provide a good starting point. On the other hand, a rather large degree of customization is often required (Partyka and Hall 2010). Numerous systems are available, each with its particular characteristics. According to Bowersox et al. (2002), the vast capabilities incorporated in many systems may be impressive, but might not be needed – ‘choose a system that handles your needs’, is their natural advice. No attempt is made here to provide an overview of existing systems, which are in constant development; the internet provides a useful platform

for updated information. Note also that, for information about the network and infrastructure, capabilities from geographical information systems (GIS) are usually required and may need to be purchased separately. For a recent survey of vehicle routing and scheduling software, see Partyka and Hall (2010).

The costs to implement a system for vehicle routing and scheduling include licence fees, installation, integration with existing systems, hardware and, sometimes, geographical information systems. As explained above, customization to the company's particular situation is normally required, which is done by the software vendor or consultants. Implementation time is typically in the order of months.

For a general introduction to vehicle routing and scheduling as well as a detailed mathematical treatment of models and solution procedures, see Toth and Vigo (2002).

9.14 Illustration of the guidelines' use and usefulness: MOMENT reviewed

The previous section completed the actual guidelines by discussing the applicability of OR techniques in transportation management. The goal of the present section is to illustrate their use and usefulness by means of the MOMENT project introduced in Section 1.6.

Among the objectives in MOMENT was the development of a model-driven decision support system that supported the establishment of Extended Enterprises of automotive component suppliers. Selecting appropriate OR techniques for this system turned out to be challenging. In the researcher's opinion, the selection process was to a certain degree characterized by fumbling, confusion and emotions. He suspects that project resources could have been employed even more effectively if techniques had been selected in a more objective, structured and informed way.

The remainder of this section briefly illustrates how the guidelines could have been used in MOMENT and uses this to propose their usefulness.

9.14.1 Use

As explained in Section 1.6, the MOMENT decision support system should support strategic decision-making in the establishment of new Extended Enterprises by addressing logistics-related issues such as plant location and distribution system design or supplier selection. Raufoss Chassis Technology, the case company in the project, was the first industrial actor to benefit from the system. Successful use of the system at Raufoss Chassis Technology was absolutely required if it was to be made available for, and used by, other suppliers.

The guidelines explain

- which precise problem situations are likely to benefit from OR techniques
- Which (advanced) OR techniques are likely to be suitable

Among the seven decision types highlighted in the guidelines as particularly suitable for OR-based decision support, mainly 'Plant location and distribution system design' can be considered to be within the scope of MOMENT. Thus, the first thing that can be learned from the guidelines is that supplier selection is less likely to benefit from advanced OR. To continue, it is sufficient to read Section 9.8, 'OR for plant location and distribution system design'. For Raufoss Chassis Technology, it provides the following understanding of technique applicability.

Applying the guidelines: Appropriateness of OR techniques in MOMENT

For plant location and distribution system design, the guidelines suggest a variety of techniques, whose applicability for Raufoss Chassis Technology is now discussed.

Deterministic optimization is mainly useful if the number of alternative network configurations is large. Raufoss Chassis Technology, however, had at that time one production plant (at Raufoss), and it was considering to establish a second plant, in the United States. This only gives two alternative plant configurations: (1) Opening the plant in the United States, or (2) increasing capacity at the existing plant. Material flows are easy to determine once this decision is taken: Serve each customer location from the closest plant. In such situations, deterministic optimization is not normally required. ‘*Spreadsheet*’ simulation can be used to analyse each alternative explicitly.

Discrete-event simulation can assess the effects of different control principles and of operational uncertainties/fluctuations on costs and performance. However, the guidelines indicate that supply chain simulations tend to be challenging and time/resource-consuming (for reasons suggested in Subsection 7.4.3). Even though MOMENT was a large EU-financed project, the resources allocated to the development of the strategic decision support system were limited. Moreover, expertise in simulations of supply chains was not easily available. Attempting to use discrete-event simulation should therefore be considered as highly risky.

Inventory theory can help estimate required inventory investments. The guidelines explain that simple, single-stage models are useful in many situations. They are often used in ‘spreadsheet’ simulations. On the other hand, multi-echelon inventory theory is not needed in Raufoss Chassis Technology’s situation because its products are produced entirely in a single manufacturing line and stored at a single location before they are directly delivered to the customers.

Gravity location models do not seem to be needed by Raufoss Chassis Technology because the locations of new plants had to be near customers’ plants.

Putting it all together, the guidelines propose for Raufoss Chassis Technology’s situation a ‘spreadsheet’ simulation, possibly including some simple inventory-theoretic models to estimate inventory investments.

Thus, the guidelines suggest that advanced OR techniques might be of limited value to support Raufoss Chassis Technology in MOMENT-related problem situations. Instead, they basically recommend a ‘spreadsheet’ simulation.

9.14.2 Usefulness

The previous subsection illustrated the *use* of the guidelines. Based on it, their *usefulness* is proposed. The guidelines’ indications are fully confirmed by what actually happened in the project. Attempts to use deterministic optimization were abandoned first, followed by an unsuccessful attempt to use discrete-event simulation. Finally, a generic spreadsheet simulation model was developed, based on Raufoss Chassis Technology’s supply chain.

Thus, with the guidelines, it was possible to correctly predict the applicability of OR techniques in MOMENT. This illustrates their usefulness: Using the guidelines, the MOMENT project team could have quickly obtained a rough understanding of OR technique appropriateness in their situation. This would have simplified the assessment and selection of OR techniques. The team could have more rapidly excluded certain OR techniques and turned to other decision support approaches. The two failed attempts to make OR work would probably have been avoided and project resources allocated even more effectively.

Based on this example, it is reasonable to assume that the guidelines can be useful in similar situations, when the use of OR techniques is considered. As an opportunity for further


research, the guidelines should be further tested and refined, as well as made more instructive and applicable.


9.15 Summary: The core elements of the guidelines

This chapter has provided an overview and discussion of the problem situations in manufacturing logistics that can benefit from OR techniques, as well as descriptions of how these techniques work. It integrates the knowledge on OR applicability developed earlier in this thesis with existing literature and theory. It highlights numerous opportunities of OR techniques, but also pinpoints limitations in order to provide an unbiased view. It is mainly written for people who need to be aware of the opportunities of OR without being OR professionals. Still, the chapter can also be of interest to OR professionals, especially those new to the field, highlighting promising application areas and containing references to numerous applications described in the literature.

The chapter is presented in the form of guidelines discussing the links from manufacturing logistics problem situations to suitable OR techniques. The guidelines are structured into seven decision types frequently supported by OR. They concentrate on the four OR techniques that – according to the present research – seem to stand for the majority of advanced OR applications in manufacturing logistics. Based on the guidelines in this chapter, a colour code can be used to indicate how popular the various links between decision types and OR techniques are (Figure 9-16).

		OR technique			
		Deterministic optimization	Discrete-event simulation	Queuing theory	Inventory theory
Decision type	Short-term production planning/scheduling	Green	Yellow	Red	Red
	Plant location and distribution system design	Green	Yellow	Red	Yellow
	Production plant design	Yellow	Green	Green	Red
	Inventory management	Red	Yellow	Red	Green
	Aggregate production and capacity planning	Green	Red	Red	Red
	Determination of production rules/policies	Red	Green	Green	Red
	Transportation management	Green	Red	Red	Yellow

 Typical OR application

 OR applications occur


 OR applications less common

Figure 9-16: A rough summary of the researcher’s understanding of OR technique applicability in manufacturing logistics, based on the research presented in this thesis.

It must, however, be strongly emphasized that this illustration merely contains indications, solely reflecting the researcher’s understanding obtained from this doctorate study. The matrix is open for discussion and further research is required to validate it. It is also very superficial and cannot be used to determine OR appropriateness in a given problem situation alone. Where each OR technique has its sweet spot, does not only depend on the decision

type, but also on other characteristics of the problem situation. Numerous such characteristics were discussed in the guidelines.

Selecting OR technique has frequently been characterized as an art (Brooks and Tobias 1996). An overall conclusion from these guidelines and the thesis more generally is, however, that it contains elements of science, where rules and guidelines can be established. It implies that, instead of emotionally loaded arguments about which technique is most appropriate for logistics and supply chain management, a detailed understanding of the problem situation should be aimed at. Technique appropriateness is then often incidental.

10 Conclusions

The core elements of the guidelines, presented at the end of the previous chapter, contain some of the main conclusions related to this thesis' research issue, the applicability of OR techniques in manufacturing logistics. The present chapter links back to the Introduction chapter and makes some more general conclusions and reflections.

After a brief review of research problems, objectives and overall design, this thesis' main contributions are clearly stated and related to research objectives. The quality of the thesis is then briefly assessed, followed by an important section on its significance and limitations. The way different groups of professionals can use it is explained next. Finally, some reflections about factors positively affecting the future of OR in manufacturing logistics are made and opportunities for further research suggested.

10.1 Research story line

Point of departure

This research has emerged from a desire to exploit the opportunities of operations research techniques in the field of manufacturing logistics. Since each technique has its own characteristics, strengths and limitations, an understanding of the situations in which each can be beneficial is crucial if they are to provide a competitive advantage. Nevertheless, a review of the literature revealed that relatively little research had addressed the applicability of OR techniques. Moreover, the issue seems to cause considerable confusion and disagreement in practice. For example, discussion about the appropriateness of simulation as opposed to optimization for logistics and supply chain problems has raged for decades (Powell 2005, Riddalls et al. 2000, Mentzer 1989). The following specific gaps have been identified:

- Little research has systematically investigated the contexts in which different OR techniques work well in order to provide help in selecting techniques
- Existing research is often of limited usefulness in practice and has not been validated empirically
- Technique selection in practice is often ad hoc and in danger of being affected by personal preferences
- Logistics professionals without OR background have little means to judge the appropriateness of OR techniques, nor are they aware of the implications of choosing a particular technique (often embedded in decision support systems such as Advanced Planning and Scheduling).

As a consequence of these gaps, there is the danger that the opportunities of OR techniques are not be fully exploited, and that manufacturing companies in practice refrain from OR-based decision support in situations where it could have provided them with a competitive advantage.

Objectives

The overall objective was therefore to *increase knowledge on the applicability of OR techniques to support decision-making in manufacturing logistics, and to provide an overview*

of such knowledge for logistics professionals without OR background. This objective was to be achieved by means of three specific objectives:

1. To identify, classify and characterize the typical OR techniques used to support manufacturing logistics in practice, and to identify and classify the manufacturing logistics decisions supported.
2. To provide empirical evidence of how the applicability of OR techniques depends on different problem situation characteristics.
3. To develop guidelines that help logistics professionals understand if and how OR techniques can support a given real-world problem situation in manufacturing logistics.

Together, these objectives should contribute to less confusion about the areas in which OR techniques work well, more effective technique selection in practice, and full exploitation of the opportunities of OR to support manufacturing logistics, ultimately leading to reduced costs and increased profits for the involved companies.

Overall research design

The overall idea to achieve these objectives was to study a large number of successful OR applications, to identify the areas in which different OR techniques were useful, to scrutinize how they were used, and to develop guidelines based on findings and existing knowledge on OR applicability. Since literature contains hundreds of descriptions of such applications, with details about the situations in which they took place, relying heavily on secondary literature was deemed appropriate. If not better than, for example, a questionnaire-based survey with its typical problems related to low response rates and question wording. Close to 200 OR applications were systematically selected from literature, providing a solid sample for studying OR applicability. For reasons explained in Chapter 7, the journal *Interfaces* and the proceedings of the *Winter Simulation Conference* were selected as the main literature sources. In addition, a number of case studies were carried out for in-depth assessment of why and how OR techniques were used. Case data was collected by means of interviews, written documentation and participation. The research objectives were achieved by synthesizing existing theory with the data collected. For objective (1) and (3), research was mainly inductive and qualitative, objective (2) called for a more quantitative, deductive research strategy.

Results

This doctorate study has led to the following main results:

- A classification and characterization of the main OR techniques used to support manufacturing logistics
- A classification of the manufacturing logistics decisions supported by OR
- A conceptual framework for studying OR applicability in manufacturing logistics
- Substantial empirical evidence of the link between problem situation characteristics and OR applicability, by means of extensive surveys and case studies.

- Guidelines for manufacturing logistics practice, providing an overview and discussion of the situations in which OR techniques can provide useful decision support, and how they provide this support.

These results will be briefly summarized in the next section.

10.2 Main contributions

This thesis has contributed to existing knowledge by developing classifications and frameworks, by empirical evidence based on surveys and case studies, as well as by guidelines for practice. The main results are now briefly resumed and linked back to the original thesis objectives.

A classification was developed of the main OR techniques used to support manufacturing logistics, consisting of deterministic optimization, discrete-event simulation, queuing theory and inventory theory. At such a high level, different techniques have different world views, support decision-making in different ways, are often practised by different people and are implemented in different types of software systems. At this level, technique distinction is therefore of interest and importance also for the field of operations management. A characterization of the techniques distinguished is also provided, based on the idea of paradigms introduced by Kuhn (1970).

Similarly, a classification of manufacturing logistics decisions supported by OR was developed. Relevant existing frameworks were used as a starting point. The main purpose of the classification is to highlight the decision types that can benefit from OR. Moreover, it is integrated with the technique classification into a framework providing a structure for investigations of the applicability of OR techniques in manufacturing logistics. This completes the first research objective.

The classifications and characterizations were developed based on existing theory and a study of a large number of OR applications described in literature. This set of OR applications also provided the sample used to obtain empirical evidence of how the applicability of OR techniques depends on different problem situation characteristics. Five such problem situation characteristics were selected based on literature, namely decision type, planning horizon, system scope, company size and industry. Findings allowed testing numerous claims made in literature about the applicability of OR (theory testing), as well as putting forward several new propositions (theory development). In addition to these surveys of application papers, three case studies were carried out for an in-depth understanding of problem situations that can benefit from OR, as well as of how OR supports them. The thesis thereby provided empirical evidence of how the applicability of OR techniques depends on problem situation characteristics, fulfilling the second research objective.

Based on the above results as well as existing theory, extensive guidelines for selecting OR techniques in manufacturing logistics were developed. These guidelines describe and discuss the situations in which the different OR techniques can often provide useful decision support. Furthermore, they contain general descriptions of common types of OR applications in manufacturing logistics. The descriptions focus on practice-relevant issues. Given a real-world problem situation in manufacturing logistics, the guidelines thus help assess if OR techniques can be a good choice for decision support. The guidelines target people who need to be aware of the opportunities of OR without being OR professionals. They are presented in

a form and language that is relevant for manufacturing logistics practice, without mathematics or computer jargon. This completes the third research objective.

In conclusion, it is the author's opinion that the three specific research objectives of this thesis have been satisfactorily completed. The overall objective, increasing knowledge on the applicability of OR techniques and providing an overview of this knowledge for logistics professionals without OR background, is therefore also considered as achieved.

10.3 Quality assessment

Section 0 provided a brief review of how research quality can be assessed. While validity and reliability provide standard measures to evaluate quantitative research that follows the 'scientific method', more qualitative research lacks such established procedures. Section 0 concluded with a set of quality criteria to be used to assess the present thesis. This is done in Table 10-1.

Table 10-1: Assessing this thesis along some quality criteria

Criterion	Assessment
Problems, issues and earlier/existing knowledge made clear	Section 1.3 specifies the issue addressed, followed by a section on research problems. Relevant existing knowledge is reviewed at numerous locations throughout the thesis. In particular, existing literature on OR applicability is reviewed in Sections 4.13 - 4.15, Subsections 5.3.1 - 5.3.4, Sections 7.1, 7.2 and Section 9.2.
Synthesis of theory and data by critical reflection	All the major contributions have been obtained by integrating existing theory with the data collected, in a way considered as purposeful from the researcher's perspective and experience.
Original contribution to existing knowledge clearly stated	The main contributions are stated in Section 10.2, with linkages back to original research objectives.
Validity and reliability	Validity and reliability issues are addressed as a part of thesis limitations in the next section.
Newness	While all contributions constitute new knowledge the comprehensive guidelines on OR applicability in manufacturing logistics (objective 3) can be considered as the major novelty.
Easily accessible language	The thesis has been written from the perspective of operations management, minimizing OR-technical jargon.

Based on this table, it is concluded that the quality of the present thesis is satisfactory. Nevertheless, every scientific work has weaknesses and limitations, which should be clearly stated. This will be done in the next section.

10.4 Significance and Limitations

10.4.1 Significance

In a research context, the term significance is mainly used in sampling theory within quantitative research. In this context, an outcome is regarded as statistically significant if differences between different groups are not just due to the fact that a random sample was used rather than the entire population (Cooper and Schindler 2003). Even though the present

this thesis contains some quantitative parts (Chapter 7), formal significance tests were not applied because the sample used was not random, but obtained on convenience grounds. It was therefore considered as more important to discuss possible sources of bias in the results, which must be remembered when attempting to generalize. This was done in Section 7.4. Note that the surveys carried out by other researchers, reviewed in Table 7-1, did not use significance tests either.

How can the significance of the more qualitative contributions of this thesis be assessed? In general, something is considered as significant if it *matters*, is *important*. In the researcher's opinion, the following elements have contributed to the significance of the present research:

1. The claims made on the applicability of OR techniques are based on a *large number of successful applications* in the real-world. As explained in Subsection 7.3.2, the journal *Interfaces* asks authors to obtain letters from the case companies verifying the actual use and resulting benefits from the OR study. Thus, while much of the earlier research on OR applicability is based on expert statements that risk to be made from biased perspectives, the present thesis is based on *evidence of what has actually worked in practice*. It is not affected by any particular OR technique preference.
2. The thesis is written from the *problem-owner's perspective*, such as operations and logistics managers. From such a perspective, it is important to quickly obtain an *overview* of the situations in which OR techniques can help, as well as how they work. Thus, rather than analyzing a particular OR technique in detail, the thesis covers the entire range of OR techniques and manufacturing logistics decisions. Other elements that underpin this thesis' problem-owner perspective are that is anchored in the operations management field, it starts from problem situations and guides to techniques, and it uses a non-technical language.

The importance of these elements was further motivated in the Introduction chapter. Murphy (2005a) recently stressed that engaging in observation and synthesis can be a fruitful path of research, especially at business schools, which educate the students who are future customers of OR. He also proposed as a concrete research opportunity to survey OR applications to better understand modelling choices in different industries.

10.4.2 Limitations

Alongside with the significance, limitations must also be clearly stated. One can distinguish between limitations in *scope* and limitations in *methodology*. The former was covered in Section 1.5 in the Introduction chapter, so focus here is on the latter. Four specific limitations are discussed. The first three are mainly related to the way knowledge was developed from surveys of application papers. The fourth emphasizes the incompleteness of the guidelines. Note that this discussion of limitations addresses issues concerning validity and reliability.

Survey samples are likely to be somewhat biased

It is not practically possible to access the total population of OR applications and to draw a random sample from it. The researcher therefore had to choose samples using nonprobability procedures (Cooper and Schindler 2003). This limits opportunities for quantitative data analysis and generalizations by means of statistical methods. Samples chosen on convenience grounds can be biased. Sources of bias in this thesis' survey samples include:

- Many OR applications are never documented in academic literature. This may be because of a lack of resources and incentives, because of non-disclosure policies of involved companies, because the applications are not considered to have enough novelty character, or because they are considered as too simple. Gass (1996), Reisman and Kirschnick (1994), and Grassmann (1986) further discuss this issue.
- Looking only at two literature sources can introduce additional bias. Some people publish their OR applications in sources other than two selected, for example in *OR Insight*, the *European Journal of Operational Research*, the *Journal of the Operational Research Society*, as well as numerous conference proceedings. Editorial preferences and the two selected sources' root in the United States can also have affected the choice of papers published.
- As far as the *Winter Simulation Conference* survey is concerned: looking at only four consecutive years cannot account for fluctuations in industry and covers, more generally, a short period.
- As far as the *Interfaces* survey is concerned: Although *Interfaces* is open for all OR techniques, its authors and readership may work more with optimization than, for example, discrete-event simulation.

Besides these sources of bias, which are due to nonprobability sampling, there is also the danger that authors of application papers exaggerate the benefits obtained from their OR applications. *Interfaces* reduces this danger by asking authors to obtain letters from the case companies verifying the actual use and resulting benefits from the OR study. Still, in some cases at least, the benefits might not be a direct consequence of using a quantitative model, but largely due to the involved OR professionals' facilitating role and logistics expertise. In such cases, the benefits would have been achieved without explicit quantitative modelling.

As a consequence of these limitations, survey results must be read, interpreted and used critically. The surveys can be said to provide a snapshot of OR applications published in two literature sources. Their samples do not allow statistical analyses or rigorous generalisations and implications must be made with care. The surveys simply provide a feel of what is going on in the wider population (see also the limitations concerning the guidelines below).

Nevertheless, it should be re-emphasized at this stage that OR applications carried out by other researchers have been used to strengthen the findings of this thesis' surveys. In particular, the empirical basis for the guidelines is much wider than the two literature sources the researcher surveyed himself.

Predicting the future by looking at the past ignores recent developments and trends

This research is based on the assumption that the study of successful past application cases provides a good means to make predictions about the applicability of OR techniques in the future. More precisely, it is assumed that what has worked before is likely to work again. Reversely, this means that what has not worked so far is not likely to work in the future either. The limitation of such an approach is that it ignores that research and development can lead to novel opportunities. For example, recent theoretical developments in stochastic programming can lead to increased use of this technique in the future (Schütz et al. 2009 present an application in the meat industry). Similarly, business trends can influence the popularity of

different OR techniques. Recent trends in inventory reductions, for example, have led to an increase in applications of inventory theory in recent years (see Appendix A).

There are no straightforward and easy-to-use classifications of the concepts used

In this research, several classifications have been developed in order to allow rigorous investigations of OR applicability. They satisfactorily satisfy Cooper and Schindler's (2003) requirements, i.e. purposefulness, exhaustiveness, mutual exclusivity and the need to be derived from a single classification principle. Some existing classifications have also been used, for example the North American Industry Classification System (NAICS).

Developing and using classifications can be difficult, ambiguous and frustrating, however. Classifying complex items such as OR models, manufacturing logistics decisions or industrial companies is not easy, and it will normally be possible to find cases of doubt. The classifications used here make no exception. Even though they proved satisfactorily robust, in the sense that most OR applications could be classified easily, some of them could sensibly be allocated to several classes. Such difficulties were already observed by Vatter (1967): 'Industry classifications are always difficult; in this day of diversification, acquisitions, and technological change, it is not easy to put a given company into the same group with very many others.'

'Correctness' and completeness of the guidelines

With hindsight, the researcher must confess that the objective of developing guidelines that cover the practice of OR for the *entire* field of manufacturing logistics has been extremely ambitious. It requires knowledge and experience in very different types of OR applications, which he as a young scientist only can have to a limited degree. He chose to study successful past case descriptions in order to 'speed up the acquisition of knowledge and experience', as suggested by Littlechild and Shutler (1991). Naturally, however, this approach could not match experience gained gradually over many years. He carried out a number of case studies as well, providing him with deeper insight, but they only cover parts of the scope of the guidelines. Certain parts of the guidelines can therefore be considered as rather superficial. Surely, experienced OR professionals are able to develop more comprehensive and detailed guidelines. The present guidelines are to be understood as a starting point, hopefully encouraging other researchers to develop them further.

In general, meta-methodological guidelines for technique choice, such as the guidelines presented in this thesis, can be criticized for doubtful validity. See, for example, how Ormerod (2005) criticizes Mingers and Brocklesby's (1997) work. Moreover, such guidelines can mistakenly 'lead to an uncritical or unwitting limiting of method choice tied to the theorized links between an a priori categorization of problem situations and the appropriateness of pre-specified methods' (Davies et al. 2005).

The knowledge contained in the guidelines is neither complete nor undisputable. If a different research design had been chosen, findings would probably have been somewhat different. Users must therefore critically reassess the guidelines' reasonableness in each particular situation. The guidelines merely provide a feel of what often seems to be the case in practice. This is emphasized by the use of fuzzy terms such as 'often', 'can', and 'is likely'. These terms indicate that the guidelines contain rules that often work, but that there are exceptions. Investigating the applicability of OR is behavioural science, not physical science. In the

former, theories do not usually constitute laws like in the latter, but simply rules where exceptions can occur.

'In a pragmatic sense, introducing methods through frameworks to participants is essential if we really want participants to have equal information and expertise to take part in discourse and decision-making. Due to the educators' partial worldviews, such introductions may be not 'perfect', not 'critical' or 'reflexive' as we expect. Yet without being introduced to, informed about, or exposed to the wide range of existing methods with the assistance of pedagogical frameworks of one kind or another, participants will be left to wait for, and to accept, whatever is delivered by 'experts' as facilitators or authorities, or they will have no other choice but to 'hit everything with whatever hammer at hand'.' (Zhu 1999)

10.5 Implications for academia and practice

'There is nothing so practical as a good theory.' (Lewin and Cartwright 1951)

The present thesis sheds light on the usefulness (applicability) of OR in manufacturing logistics. It contributes to a theory of the practice of operations research, which has been requested by Murphy (2005a, 2005b, 2005c).

For practice, an important implication is that comprehensive guidelines are now available that help understand in which situations to turn to OR techniques for decision support. They will ultimately lead to better decision-making in manufacturing logistics. From an academic perspective, an overall implication of the present thesis is that the applicability of OR techniques (and other decision support approaches) constitutes a research area in its own right, with plenty of unexploited opportunities (see the Further Research section below).

More specific implications are now outlined separately for the different groups of professionals defined in Section 1.9 in the Introduction chapter.

Logistics professionals. The guidelines highlight typical opportunities to apply OR in manufacturing logistics, helping logistics professionals understand if and where OR can provide them with a competitive advantage. For example, large multi-plant companies desiring centralized planning/coordination can frequently benefit from deterministic optimization, both at the strategic, tactical and operational level. Discrete-event simulation seems to have its sweet spot at the inside of a production plant. Multi-echelon inventory theory can help reduce inventory levels in supply chains with semi-finished and finished products being stored at several locations before they finally reach the customer. The guidelines also help logistics professionals understand and judge the usefulness of OR models proposed by OR professionals.

Software developers. The present study helps the software industry develop model-driven decision support systems in practically relevant areas. While it is too early to make any solid conclusions, it for example seems that discrete-event simulations of supply chains may never enjoy the same success as discrete-event simulation focusing on the inside of a production plant. Software developers must also be aware that even in areas frequently supported by OR, the development of *standardized* software systems may not succeed. This has been evidenced by limited success of Advanced planning and scheduling systems (APS).

OR practitioners. The study helps OR practitioners, especially those new to the field, judge if a problem situation can benefit from OR, and which OR techniques are likely to be appropriate in the given problem situation. This way, they can better select promising customers, application areas and techniques. This maximizes the chance that their projects succeed. Trying to use deterministic optimization to schedule a traditional (non-automated) job/flow shop with many products, many machines, and complex job routings, for example, can be a risky endeavour. The present thesis can also encourage OR practitioners to publish OR applications in less common areas, such as inter-organizational planning.

OR professionals working with theoretical development. For these people, the study can point out practice-relevant directions for further research. It also pinpoints areas where OR techniques so far has had more limited practical impact, such as deterministic optimization for line balancing. Researchers may investigate the reasons for this limited applicability in order to develop more practice-oriented models. Researchers can also build upon the present work and provide further evidence of OR applicability.

Educators. Educators, finally, can use the present thesis when teaching about the practice of OR. It helps them select practice-relevant topics, as well as find relevant cases when they desire to accompany theoretical treatment of a topic with real-world cases.

In particular, all these professionals can use appendices A and B as structured references to over 180 OR applications in manufacturing logistics. These appendices provide them with relevant material about previous cases in numerous different problem situations and industries.

10.6 The future of OR in manufacturing logistics

So far in this thesis, successful past cases have been studied to understand the role of OR in manufacturing logistics. The present section takes a different approach and presents a number of recent trends which can positively affect its role in the future.

Visibility and information sharing

In recent years, there has been increased focus on visibility and information sharing across business units and supply chains (Marufuzzaman 2006, Lehtonen et al. 2005, Montgomery et al. 2002, Lee et al. 2000). Company data, which used to be scattered across numerous legacy systems, is now collected centrally and made available in larger parts of the supply chain, continuously and in real-time. New technologies, such as the Internet and RFID (Radio Frequency Identification), are enablers of this trend (Gaukler and Seifert 2007). For OR, this means faster and better availability of more data. One of the obstacles to OR implementation, the lack of data (see Section 4.14), can thereby be reduced. OR can help decision-makers make sense of their data by evaluating ever-growing databases and calculating effective plans.

Globalization

A second major trend is globalization (Simchi-Levi et al. 2008, Lévy 2007, WTO 2005, Russell and Taylor III 2003). Increasingly companies source raw materials and components worldwide, flag out manufacturing, and sell their products in many different countries (Christopher 2005). This leads to more complex and costly transportation and material flows, longer lead times, larger amounts of inventory in the supply chain, higher uncertainty and variability and higher risk. Manufacturing companies must therefore put more and more emphasis on efficient design and management of their global supply chains (Ghiani et al.

2004). OR techniques are able to address these issues. Deterministic optimization helps design cost-effective production and distribution networks. It supports tactical supply chain planning by determining required capacity expansions, production rates and the build-up of seasonal stock. Multi-echelon inventory theory helps decide where in the supply chain to keep how much inventory so that a desired level of product availability is achieved at lowest systemwide inventory cost. With globalization, the relevance of these techniques can be expected to further increase.

Lead time reduction

Shorter product life cycles, focus on inventory reductions, volatile markets and higher competitive pressure require companies to act quickly (Christopher 2005, Rollins 1998). This has led to increased focus on lead time reduction, including decision-making lead time (Huber 2004). At the same time globalization, new technology and improved visibility lead to a growing number of alternative plans and solutions, increasing the complexity of decision-making. OR can reduce planning lead times significantly by automating repetitive routine tasks, thereby allowing decision-makers to concentrate on non-routine tasks. It can quickly explore and compare numerous plans and solutions without the need to test them in the real system. This capability is not only time-saving in operational planning; it also speeds up and improves process and supply chain design (tactical/strategic), leading to more cost-effective solutions and shorter times-to-market.

Systems view

Finally, recent years have witnessed increased focus on solutions that are efficient and cost-effective for the system as a whole (Simchi-Levi et al. 2008, Moon and Kim 2005). Emphasis is on minimizing total systemwide costs, thereby avoiding sub-optimization of functional departments or individual costs, such as production or transportation costs. Such a systems view lies at the heart of OR (see Section 4.4). OR explicitly addresses conflicting objectives and trade-offs, such as the trade-off between inventory costs and reordering costs. It thereby supports the design of solutions that minimize systemwide costs.

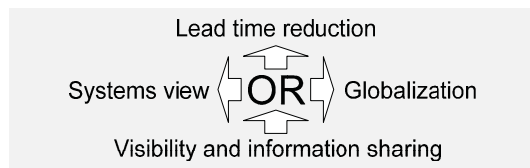


Figure 10-1: This figure illustrates the link between OR and some trends in manufacturing logistics. The arrows signify ‘supports’.

Figure 10-1 summarizes the link between OR and the four trends described. The arrows in the figure signify ‘supports’. The trends suggest that OR can play a significant role in manufacturing logistics also in the future. However, as explained at several occasions, OR is not a panacea for all problems. In order for OR to be successful, it is crucial to understand which problem situations can benefit from it. This has been the objective of this thesis. The next section finalizes it with some suggestions for further research.

10.7 Opportunities for further research

There are several opportunities for further research that follow naturally from this thesis. This final section first presents opportunities related to the applicability of OR techniques and other decision support approaches. Some lines are then devoted to *how* such research could be carried out, i.e. alternative research designs. The section concludes with some more general research opportunities related to the use of models in practice.

Applicability of OR to support decision-making

This thesis has only provided a rough overview of the situations in which OR techniques work well. There is a need for more detailed characterizations of these situations. Problem situation characteristics that crucially affect the appropriateness of different OR techniques should be identified, for example by means of cross-case pattern matching in the applications described in *Interfaces*. In order to increase the validity of findings, additional OR applications should be studied. A more detailed classification of OR techniques should also be used. Specific questions that could be addressed include:

- How does the use of OR techniques depend on the manufacturing process type?
- Is it possible to say in which situations deterministic optimization is the ‘right’ choice for short-term production planning/scheduling in supply chains, and in which situations multi-echelon inventory theory provides a better alternative? This research opportunity has also been suggested by de Kok and Fransoo (2003).
- In which situations can discrete-event simulation beneficially support decision-making at the supply chain level?
- Graves and Willems (2003) present two types of inventory models and ask for an empirical study of how good the decision support is that each of them provides: ‘The stochastic service and guaranteed-service models offer two different perspectives on how the world works. Can we determine which is right? Can we say anything about which is more common? Is either of them right? Or is there a better perspective? We hope that some future research will be able to conduct a careful empirical study of how well these models match reality, as well as how good is the decision support that they provide.’

Findings should be collected and presented as practice-oriented guidelines. This thesis’ guidelines also need to be further tested, refined and made more instructive and applicable. Well-elaborated guidelines can be implemented in expert systems. According to Ortolano and Perman (1990), providing assistance in selecting models is a particularly promising area for expert systems. Such work is not only required in manufacturing logistics, but also in other fields, such as health care and finance.

Applicability of other approaches to management and decision support

The applicability of other management approaches should also be investigated. There are, for example, books reporting on the success of business process reengineering, total quality management and lean manufacturing. The fields of artificial intelligence and management accounting also provide numerous approaches to decision support. Little research has tried to characterize the situations in which these and other approaches are suitable. Today, lacking understanding of the applicability of these approaches leads to discussions and even arguments between respective advocates. Different approaches are seen as competing against

each other, when they might actually be complementary. For managers, this lacking understanding of when each approach works well is confusing. In his famous article ‘What is the right supply chain for your product?’, Fisher (1997) writes ‘Why haven’t the new ideas and technologies led to improved performance? Because managers lack a framework for deciding which ones are best for their particular company’s situation.’ His article is an excellent example of the kind of research required. It provides criteria to determine which management approach, lean or agile, is most suitable for a given supply chain.

Research designs

Different research designs are available to carry out the research suggested above. *Expert interviews*, *case studies* and *action research* should be used to develop new knowledge on the applicability of decision support approaches (theory generation). Meredith (1998) and Eisenhardt (1989) discuss the use of case studies for theory generation. They are well-suited to uncover contextual conditions (Yin 2003), such as characteristics that crucially affect the applicability of different decision support approaches. Questionnaire-based surveys might be less suitable for this purpose, because the number of questions that can be asked (and hence the number of characteristics that can be studied) must be restricted and known in advance.

On the other hand, surveys can be used to test and validate theory. The practice-papers published in *Interfaces* can again be used, as well as additional sources, for example *Management Science*, *OR Insight*, the *European Journal of Operational research*, the *Journal of the Operational Research Society*, *Harvard Business Review*, and various conference proceedings. Well-administered questionnaires can be sent to manufacturing companies, consulting companies and software vendors. Comparing and combining the findings from an increasing number of studies will lead to more and more solid conclusions.

Other research opportunities related to the practice of OR

Asking in which situations OR techniques work well is research on the practice of OR. Other opportunities of such research include:

- Investigate how models interact with humans and affect the way decisions are made. Fuglseth and Grønhaug (2003), for example, assess how the use of quantitative models influences strategic decision-making. In production scheduling, there is a need for research on the interaction between the scheduling system and the human scheduler.
- Publish further descriptions of OR applications in *Interfaces* as well as other journals and literature sources. In particular, applications in less common areas need to be published in order to continuously reveal novel opportunities to apply OR. On the other hand, also failed OR initiatives should be reported and analysed because they can provide important insights about critical success factors and pitfalls to avoid.
- Develop guidelines supporting not only technique selection, but also the remaining steps in the process of using OR for decision support (see Section 4.8), such as problem formulation, finding the right trade-offs between model accuracy and model simplicity, making companies willing to use models etc.

The ultimate goal of research on the use of decision support approaches is to help companies make better decisions, leading to reduced costs and increased competitiveness.

10.8 Summary

This chapter has rounded off the present thesis with some final conclusions and reflections. This thesis' main contributions are classifications, characterisations, empirical evidence and guidelines related to the applicability of OR techniques in manufacturing logistics. Thesis objectives are thereby considered as achieved and its quality deemed satisfactory. Nevertheless, it has its limitations, especially the fact that the sample of OR applications studied was drawn on convenience grounds, and that the guidelines can be considered as rather superficial. The thesis makes a contribution to a theory of the practice of OR, helping logistics professionals, software developers, OR professionals and educators understand in which situations the different OR techniques can provide added value. This chapter has also presented a number of trends in logistics and business that can positively affect the future of OR, namely information sharing, globalization, lead time focus and a systemwide cost reduction perspective. Finally, the importance of additional research on the applicability of OR and other decision support approaches has been emphasized. Numerous specific paths for further research have been suggested, involving qualitative as well as more quantitative research strategies.

Appendix A

In this appendix, each OR application included in the survey of *Interfaces* papers is classified according to decision type, industry and OR technique. Note that if a paper describes an OR application that supported several decision types, or if several OR techniques were used, its reference appears multiple times.

	Deterministic optimization	Discrete-event simulation	Queuing theory	Inventory theory	Miscellaneous
Short-term production planning/scheduling					
Food manufacturing	(Bixby et al. 2006) (Brown et al. 2002) (Brown et al. 2001) (Portougal 1997) (Taube-Netto 1996)				
Apparel manufacturing	(Bowers and Agarwal 2007) (Bowers and Agarwal 1995)				
Paper manufacturing	(Murthy et al. 1999)				
Printing and related support activities	(Ahire et al. 2007) (Katok et al. 2001b)				
Chemical manufacturing	(Lee and Chen 2002) (Olson and Schmiederjans 2000)				
Primary metal manufacturing	(Pradenas et al. 2006) (Dawande et al. 2004) (Sinha et al. 1995)				
Fabricated metal product manufacturing	(Katok and Ott 2000)				
Machinery manufacturing	(Keefer 2002a)	(Flanders and Davis 1995)			
Computer and electronic product manufacturing	(Loveland et al. 2007) (Denton et al. 2006) (Leachman et al. 2002) (Lyon et al. 2001) (Bermon and Hood 1999)	(Leachman et al. 2002) (Mollaghasemi and LeCroy 1998) (Brinkley et al. 1998)		(De Kok et al. 2005)	(Demeester and Tang 1996)
Transportation equipment manufacturing	(Leachman et al. 1996) (Denizel et al. 2007) (Vandaele et al. 2000)		(Vandaele et al. 2000)		

	Deterministic optimization	Discrete-event simulation	Queuing theory	Inventory theory	Miscellaneous
Plant location and distribution system design					
Food manufacturing	(Gupta et al. 2002) (Yoshizaki et al. 1996) (Taube-Netto 1996)				
Beverage and tobacco product manufacturing	(Chollette 2007) (Köksalan and Süral 1999)				
Chemical manufacturing	(Dauzère-Péres et al. 2007) (LeBlanc et al. 2004) (Keefer 2002b) (Gupta et al. 2002) (Sery et al. 2001) (Camm et al. 1997)	(Gupta et al. 2002)		(Gupta et al. 2002)	
Plastics and rubber products manufacturing	(Tyagi et al. 2004)				
Primary metal manufacturing	(Ulstein et al. 2006) (Mondschein and Schilkret 1997)				
Computer and electronic product manufacturing	(Laval et al. 2005) (Arnizen et al. 1995)	(Lin et al. 2000)	(Lin et al. 2000)		(Laval et al. 2005)
Transportation equipment manufacturing	(Fleischmann et al. 2006) (Karabakal et al. 2000)	(Karabakal et al. 2000)			
Industry not specified	(Keefer et al. 2003) (Panchalavarapu and Jeray 2003)				
Production plant design					
Food manufacturing	(Rajaram et al. 1999)	(Rajaram et al. 1999)	(Liberopoulos and Tsarouhas 2002)		
Wood product manufacturing		(Mullens and Toleti 1996)			

	Deterministic optimization	Discrete-event simulation	Queuing theory	Inventory theory	Miscellaneous
Chemical manufacturing		(Gupta et al. 2002) (Watson 1997) (Keefer 1997)			
Computer and electronic product manufacturing	(Leachman et al. 2002) (Bermon and Hood 1999)		(Burman et al. 1998)		
Transportation equipment manufacturing	(Denton et al. 2007)	(Alden et al. 2006) (Patchong et al. 2003) (Kekre et al. 2003) (Pfeil et al. 2000)	(Alden et al. 2006) (Srinivasan et al. 2003) (Patchong et al. 2003) (Kekre et al. 2003) (Vandaele et al. 2000)		(Alden et al. 2006)
Inventory management					
Printing and related support activities				(Emsermann and Simon 2007) (Katok et al. 2001a)	
Chemical manufacturing				(Bossert and Willems 2007)	
Machinery manufacturing				(Keene et al. 2006) (Troyer et al. 2005)	
Computer and electronic product manufacturing		(Fleischmann et al. 2003) (Lin et al. 2000) (Cohen et al. 1999)	(Lin et al. 2000)	(Khawam et al. 2007) (Cohen et al. 2006) (Bangash et al. 2004) (Kapuscinski et al. 2004) (Billington et al. 2004) (Fleischmann et al. 2003) (Cohen et al. 1999) (Lee and Billington 1995)	
Electrical equipment, appliance, and component manufacturing				(Gorman and Ahire 2006)	
Transportation equipment manufacturing				(Denton et al. 2007)	

	Deterministic optimization	Discrete-event simulation	Queuing theory	Inventory theory	Miscellaneous
Aggregate production and capacity planning					
Food manufacturing	(Gupta et al. 2002) (Brown et al. 2001) (Schuster and Allen 1998) (Taube-Netto 1996) (Gupta et al. 2002) (Keefer 2002b) (Tyagi et al. 2004)	(Gupta et al. 2002)		(Gupta et al. 2002)	
Chemical manufacturing					
Plastics and rubber products manufacturing					
Computer and electronic product manufacturing	(Denton et al. 2006) (Leachman et al. 1996) (Arnitzen et al. 1995) (Gazmuri and Maturana 2001)	(Linton and Johnston 2000)			(Linton and Johnston 2000)
Electrical equipment, appliance, and component manufacturing					
Determination of production rules/policies					
Food manufacturing	(Rajaram et al. 1999)	(Rajaram et al. 1999)			
Wood product manufacturing		(Mullens and Toleti 1996) (Ahire et al. 2007)			
Printing and related support activities					
Primary metal manufacturing	(Denton et al. 2003)				
Computer and electronic product manufacturing		(Tayur 2000)			(Leachman et al. 2002)
Transportation equipment manufacturing		(Alden et al. 2006)	(Alden et al. 2006) (Srinivasan et al. 2003) (Vandaele et al. 2000)	(McKenzie and Jayanthi 2007)	(Alden et al. 2006)
Transportation management					
Food manufacturing	(Martin 1998) (Adenso-Diaz et al. 1998) (Murthy et al. 1999) (Bausch et al. 1995)				
Paper manufacturing					
Petroleum and coal products manufacturing					

	Deterministic optimization	Discrete-event simulation	Queuing theory	Inventory theory	Miscellaneous
Chemical manufacturing	(Dauzère-Pères et al. 2007)				
Miscellaneous					
Wood product manufacturing		(Wagner et al. 1996)			
Chemical manufacturing	(Sandholm et al. 2006)	(D'Alessandro and Baveja 2000)			
Computer and electronic product manufacturing	(Shirodkar and Kempf 2006) (Metty et al. 2005)	(Lin et al. 2000)	(Lin et al. 2000)		

Appendix B

In this appendix, each discrete-event simulation application included in the survey of the proceedings of the *Winter Simulation Conference* is classified according to decision type and industry. As in appendix A, note that, if a paper describes an OR application that supported several decision types, its reference appears multiple times.

	Discrete-event simulation
Short-term production planning/scheduling	
Apparel manufacturing	(Joines et al. 2003)
Primary metal manufacturing	(Finke et al. 2002)
Fabricated metal product manufacturing	(Marvel et al. 2005)
Computer and electronic product manufacturing	(Arisha and Young 2004), (Chong et al. 2003)
Transportation equipment manufacturing	(Greenwood et al. 2005)
Miscellaneous manufacturing	(Lehtonen et al. 2003)
Plant location and distribution system design	
Transportation equipment manufacturing	(Dalal et al. 2003)
Industry not specified	(Jain and Leong 2005)
Production plant design	
Wood product manufacturing	(Baesler et al. 2004), (Baesler et al. 2002)
Printing and related support activities	(Muller et al. 2002)
Chemical manufacturing	(Chu et al. 2005), (Saraph 2003), (Saraph 2002), (Gonzales-Lujan et al. 2002)
Primary metal manufacturing	(Thomas et al. 2002)
Fabricated metal product manufacturing	(Mosca et al. 2005), (Williams and Chompuming 2002)
Machinery manufacturing	(Ali et al. 2005)
Computer and electronic product manufacturing	(Jadhav and Smith 2005), (Murray and Miller 2003), (Shikalgar et al. 2003), (Aybar et al. 2002), (Shikalgar et al. 2002)
Electrical equipment, appliance, and component manufacturing	(Hasgül and Büyüksünetci 2005)
Transportation equipment manufacturing	(Grimard et al. 2005), (Maas and Standridge 2005), (Faget et al. 2005), (Ingemansson and Oscarsson 2005), (Gujarathi et al. 2004), (Lu et al. 2003), (Lu and Sundaram 2002), (Choi et al. 2002), (Patel et al. 2002)
Industry not specified	(Altinkilinc 2004)
Inventory management	
Computer and electronic product manufacturing	(Morrice et al. 2005), (Cao et al. 2003)
Transportation equipment manufacturing	(Maas and Standridge 2005), (Dalal et al. 2003)
Industry not specified	(Jain and Leong 2005)
Determination of production rules/policies	
Printing and related support activities	(Patterson et al. 2002)
Chemical manufacturing	(Chu et al. 2005), (Saraph 2003), (Saraph 2002)
Nonmetallic mineral product manufacturing	(Jacobs et al. 2005)
Primary metal manufacturing	(Türkseven and Ertek 2003), (Thomas et al. 2002)
Fabricated metal product manufacturing	(Marvel et al. 2005), (Mosca et al. 2005), (Williams and Chompuming 2002)
Computer and electronic product manufacturing	(Jadhav and Smith 2005), (LeBaron and Domasche 2005), (Shikalgar et al. 2003), (Govind and Fronckowiak 2003), (Sunkara and Rao 2003), (Potti and Gupta 2002), (Aybar et al. 2002), (DeJong and Wu 2002), (Jimenez et al. 2002), (Shikalgar et al. 2002),

Appendix B

	(Smith et al. 2002)
Transportation equipment manufacturing	(Grimard et al. 2005), (Mane et al. 2002), (Choi et al. 2002))
Industry not specified	(Farahmand and Balasubramanian 2002)
Transportation management	
Transportation equipment manufacturing	(Dalal et al. 2003)
Miscellaneous	
Computer and electronic product manufacturing	(Ghosh et al. 2005)

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