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# Master's degree thesis

**IP502009 MSc thesis, discipline oriented master**

**Collaborative robots – a process technology strategy to enable  
Leagile Manufacturing**

10002/ Stig M. Henriksen

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## **Lean manufacturing and cloud connected collaborating robots – How to optimize industrial performance?**

### **Introduction**

The concept with Robots working alongside or in close proximity to humans appears to reach a break through. Robots working side-by-side with human are a growing reality in contrast to earlier days where robots were operating in protected areas restricted with fences around.

In the past it was often about replacing the work of the human with robots, but nowadays it is more about using the robot as an intelligent assistant.

Effective lean manufacturing systems use both automated and manual processes, and it is important to find the right balance and the right type of automation.

Fixed and fully automated production cells are cost and time consuming to reconfigure due to change in market needs. Today's smaller lot sizes and greater demands for customization of products provides collaborating robots a big advantage due to flexibility and adaptability.

The advantage of the human-robot collaboration is the robot's strength due to speed, preciseness and endurance and the human's strength due to flexibility and handling upcoming problems (intelligence).

High performance sensors and intelligent control system with advanced and sophisticated software will make this cooperation between human and robots possible to achieve the most efficient and sustainable production of tomorrow.

Collaborating robot systems can be divided into two groups where both robot and human are working in the same workspace:

- Workplace sharing systems
- Workplace and time sharing systems

In workplace sharing systems human and robot do separate tasks in the same workspace. This to be in accordance to the workload leveling.

The configuration may be:

- Robot performing a handling task and operator performing an assembly task.

OR

- Robot performing an assembly task and operator performing a handling task.



Figure 1. Time distribution between human and robot in workplace sharing system

In workplace and time sharing systems human and robot share work on the same tasks in the same workspace. In addition to avoiding collision with the human, the robot also has to interact with the human to perform the shared tasks.

The configuration may be:

- Robot performing a handling task and operator performing an assembly task.
- OR
- Robot performing an assembly task and operator performing a handling task.
- OR
- Robot and operator performing an assembly task.
- OR
- Robot and operator performing a handling task.

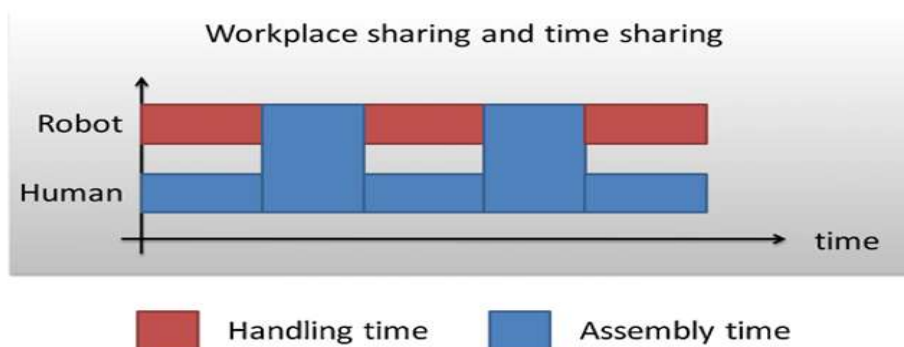


Figure 2. Time distribution between human and robot in workplace and time sharing system.

Motivation factor for the industry to invest in automation and embrace this technology is the quality improvements due to the robot’s preciseness, more effective production due to the robots speed, and by let the robots do the tasks which is not suitable for human by an ergonomic point of view. By this we can increase the efficient, capacity, quality and product variation and at the same time reduce the production cost.

By using a cloud-based architecture supporting smart devices as robot cells we will achieve a more modular and re-configurable production framework, and robots, sensors and other equipment are communicating with each other and exchange data.

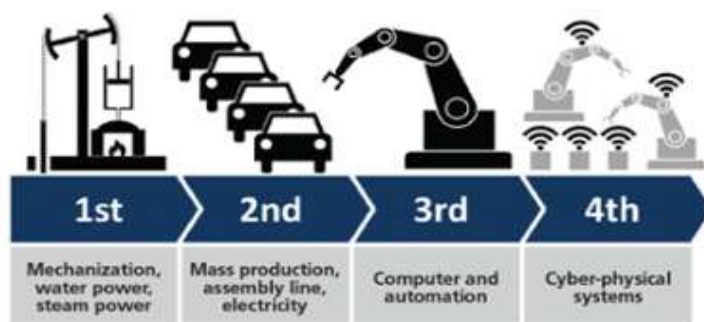


Figure 3. Showing the 4.0 “industrial revolution. (By Christoph Roser at AllAboutLean.com).

To support lean mindset fully, cloud connection between different production lines and departments in the company to achieve the best possible synchronization of the production and achieve better control on all goods flowing through the company at any time. In addition, the possibility to generate statistic reports on the systems performance and deviation due to all information available in the interconnected production system.



Figure 4 – Automated production (Ekornes AS)

### **Motivation**

Declare and develop a concept for lean manufacturing using cloud-connected Collaborative Robots to improve the industrial performance.

Today's smaller lot sizes and greater demands for customization of products provides collaborating robots a big advantage due to flexibility and adaptability.

Traditional fixed and fully automated production cells are cost and time consuming to reconfigure due to change in market needs.

The advantage of the human-robot collaboration is the robot's strength due to speed, preciseness and endurance and the human's strength due to flexibility and handling upcoming problems (intelligence).

This is also a motivation factor for the industry to invest in this type of automation and embrace this technology. Quality improvements due to the robot's preciseness, more effective production due to the robots speed, and by let the robots do the tasks which is not suitable for human by an ergonomic point of view. By this we can increase the efficient, capacity, quality and product variation and at the same time reduce the production cost.

## Scope

Optimize performance on the collaborative robot cells due to minimize non-added value activities in industries with small and medium scale production using small-scaled collaborative robot cells. Determine how well collaborative robot cells fits into a lean manufacturing environment, study the workload leveling between human and robot in a collaborative robot cell, takt time, material flow and information flow. Also to study how the collaborative robot cells will apply the cloud to achieve benefits of distributed signaling due to monitoring and improvements of the manufacturing process in industries with small and medium scale production.

## Objectives

Determine how well collaborative robot cells fits into a lean manufacturing environment, study the workload leveling between human and robot in a collaborative robot cell, and how the robots will apply the cloud to achieve benefits of distributed signaling due to monitoring and improvements of the manufacturing process in the mechanical industry.

Research question: Lean manufacturing and cloud connected collaborating robots – How to optimize industrial performance?

Divide research question into 3 main topics:

- Lean manufacturing.
- Cloud connected collaborative robotic cells.
- Application – Small-scaled collaborative robot cells.  
Optimize performance on the collaborative robot cells due to minimize non-added value activities in industries with small and medium scale production using small-scaled collaborative robot cells.

## Milestones:

Tasks:

1. Identification of topics content.
2. Literature review on state of the art for industrial cloud connected collaborative robots in a lean environment.
3. Study the methodology for optimize industrial performance. Cloud connected collaborative robot station into a lean environment.
4. Analysis of the above topics.
5. Results and discussion.
6. Writing.



**Schedule**

Task	Name	15 Jan	1 Feb	15 Feb	1 Mar	15 Mar	1 Apr	15 Apr	1 May	15 May	1 Jun
1.1	1, 4	█									
1.2	2, 4	█									
1.3	3, 4	█									
2.1	2, 3, 7		█	█	█						
2.2	4, 5, 7			█	█	█					
2.3	4, 7						█				
3.1	6, 7							█			
4.1	6, 7, 8								█		
4.2	4, 6, 7, 8		█	█	█	█	█	█	█	█	█

In addition to the specified tasks, a conference paper will be handled at the end of the research.

**Deliveries:**

Preliminary Thesis (06<sup>th</sup> March)  
Final Thesis + Article (19<sup>th</sup> June)

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## Abstract

The collaborative approach where humans use robots as an intelligent assistant in the same workspace to achieve a common goal have become a powerful tool.

Collaborative robots support quick adaptation to changing requirements, by quick reconfigurability to a new product- or process mix, and quick adaptability to different processes in the production line. In other words, they enable flexibility in the production processes; also known under the concept of ‘agility’ in the supply chain literature. At the same time, cobots have shown to enable lean processes in the production line by reducing cost due to elimination of waste. For example, the cobots enable reduced installation and reconfiguring time, less process complexity, prevent unused employee creativity and they need less manufacturing space.

By combining the lean and agile manufacturing paradigms in the supply chain, the benefits from both worlds can be achieved.

This thesis explores the collaborative robot’s ability, as a process technology strategy, to enable leagile manufacturing (by extrapolating lean and agile) with improved performance from flexibility and lean processes, in industrial environments with high product- and process variety. Further to show how to implement the product variety across the supply chain, including the manufacturing processes. The findings are summarized by a conceptual framework for leagile manufacturing through collaborative robots. This is achieved by triangulating an explorative literature study (by reviewing supply chain management and production systems literature and real-life cases) and expert interviews.

**Keywords:** Collaborative Robots, Leagile Manufacturing, Lean Manufacturing, Agile Manufacturing, Flexibility, Reconfigurability.

## Preface

This thesis represents my last semester of my Master of Science degree in Product and System Design at NTNU and consist of the topics collaborative robots and Leagile manufacturing.

I have always had an interest in automation, and when I started my master thesis, all the technical aspects surrounding cobots was something I looked forward to research. During this work, I have developed a great interest in the “business systems” lean/agile manufacturing. I believe this have a great future in the industry years to follow and is worth further research. Collaborative robots and leagile manufacturing is truly a topic I want to develop myself and gain further knowledge in. I believe it’s an important competence to possess in relation to the increasing global competition with smaller lot sizes, products with shorter life cycles and increased demand for customization.

## Acknowledgement

I would like to express my gratitude to my academic supervisors Ola Jon Mork, Irina-Emily Hansen and Hajnalka Vaagen for the comments, remarks, engagement and tremendous support through the learning process of this master thesis.

Also, I highly appreciate the help and support from those who contributed to the interviews in the thesis.

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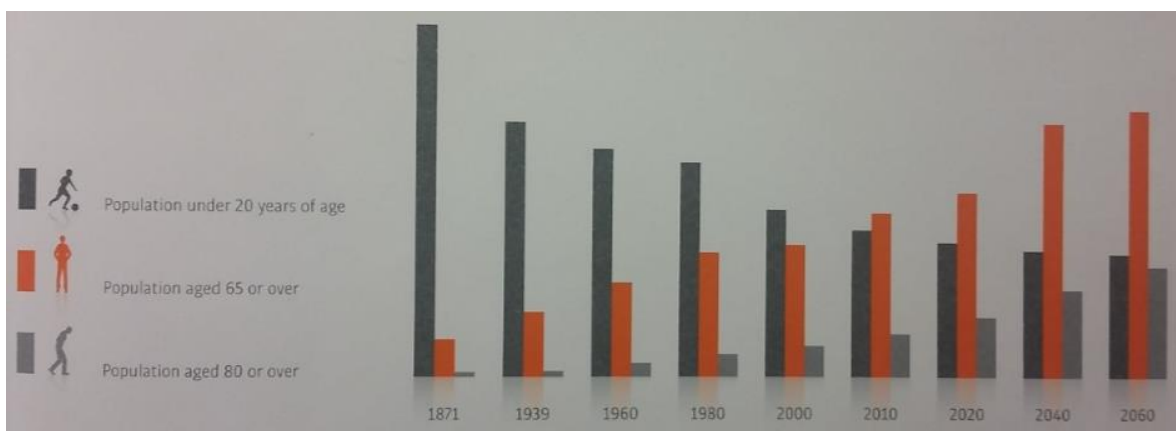
## Abbreviations

HMI	Human Machine Interface
PLC	Programmable Logical Controller
GUI	Graphical User Interface
COBOT	Collaborative Robot
HRC	Human Robot Cooperative
UR	Universal Robots
Leagile	Lean and Agile
IOT	Internet of Things
IIOT	Industrial Internet of Things
WIP	Work In Process
JIT	Just In Time
DP	Decoupling Point
DML	Dedicated Manufacturing System
FMS	Flexible Manufacturing System
RMS	Reconfigurable Manufacturing System

# 1 Introduction

## 1.1 Background and Motivation

Today's society in the industrial nations is facing falling birthrates and increasing life expectancy (Figure 1-1). It is hard to predict the productivity in the future, but digitalization of manufacturing processes and smarter machines will largely be able to make people much more effective than all generations before them. More intelligent production technology as cooperative robots that works closely with the workers will be able to ensure that experienced older employees can further provide an active contribution in the workplace (Reuter 2016).



**Figure 1-1. Population in Germany from 1871 to 2060. Source: German Federal Statistical Office.**

The increasing global competition requires smaller lot sizes, products with shorter life cycles and increased demand for customization (Christopher et al. 2006). This provides collaborating robots a big advantage due to flexibility and adaptability (Kruger et al. 2009).

Because of this new global market, it is according to the author important to reveal how to increase the industrial performance for companies producing high variety products.

The advantage of the human-robot collaboration is the robot's strength due to speed, preciseness and endurance and the human's strength due to flexibility and handling upcoming problems by human intuition and intelligence (Kruger et al. 2009). This cooperation between human and robots make it possible to achieve the most efficient and sustainable production of tomorrow (Kruger et al. 2009). By this using both automated and manual processes to find the right balance and the right degree of automation (Harris & Harris 2008).



Robots working side-by-side with human are a growing reality in contrast to earlier days where robots were operating in protected areas restricted with fences around (Faber et al. 2015), (PWC 2014). Many of the today's applications require the benefits both humans and robots can contribute. In the past it was often about replacing the work of the human with robots, but nowadays it is more about using the robot as an intelligent assistant (Kruger et al. 2009), (PWC 2014).

Compared to collaborative robots, the traditional fixed and fully automated production cells are cost- and time consuming to reconfigure to changing market needs (Kruger et al. 2009).

Collaborative robots have shown a quick response to changing requirements and an ability to reconfiguration of the production line with low set up cost and low time consumption, proved by the explorative case studies (Scott Fetzer 4.1.1), (Continental Auto 4.1.3), (Cooperation human-robot 4.1.5) and in literature (Kruger et al. 2009), (PWC 2014).

Using agile manufacturing where we need flexibility and lean manufacturing where we need standardization and leveling scheduling. This is in manufacturing theory often referred to as Leagile manufacturing. Both paradigms have their strengths and limitations, and by carefully combine them in relation to the correct supply chain strategy will provide a complementary positive effect (Naylor et al. 1999). The decoupling point between lean and agile will be functioning as an inventory buffer between demand for a high variety of components and level production schedule for low variety of components. By this having the correct supply chain strategy and combine lean and agile paradigms carefully, companies can achieve significant benefits from both worlds (Naylor et al. 1999).

The different supply chains are strongly related to associated manufacturing systems which transforms raw material into products (Bi et al. 2008). By combining both lean and agile approach, the Reconfigurable Manufacturing System (RMS) is applied (Varga & Covacs 2016). The modular building blocks and focus on part family production make RMS easily upgradable due to add/remove new cobot cells or supply with new functionalities to existing cell. This will prevent the obsolescence of the manufacturing system and provide the desired flexibility through scalability and reconfiguration as needed to meet the market requirements (Elmaraghy 2006), (Mehrabi et al. 2000).

Explorative case studies have been used to provide new understanding on a new problem with limited research to generate new principles and ideas that need further research. Further it is developed a conceptual framework for showing how to enable leagile manufacturing by using

collaborative robots as a process technical strategy, and by this shows how to implement the product variety across the supply chain, including the manufacturing processes.

By supplementing collaborative robots as the *process technology* within a Leagile manufacturing we will achieve improved performance from flexibility and lean processes, in industrial environments with high product- and process variety.

## 1.2 Purposes

Now that technology of collaborative robotics is present and is starting to mature, it is possible for enterprises with high product variety in their production to automate many of their processes using collaborative robots. Most of the suppliers of such robots has a strong focus on module based, easy installation and high intuitiveness compared to operate them.

The operators do not necessarily need to be experts to use them, and programming effort, installation- and training time is greatly reduced (Scott Fetzer 4.1.1), (Continental Auto 4.1.3). This means that the companies can hold their expertise “in-house” and not be dependent on expensive third party experts when changes in production (Continental Auto 4.1.3).

The main purpose for this study is to explore the collaborative robots’s ability, as a process technology strategy, to enable leagile manufacturing with improved performance from flexibility and lean processes, in industrial environments with high product- and process variety. Further summarize the findings by a conceptual framework for leagile manufacturing through collaborative robots, and by this show how to implement the product variety across the supply chain, including the manufacturing processes.

## 1.3 Problem areas

Implementations of automated processes can in many cases cause higher degree of complexity and high investment cost. It is therefore important to find the right balance of automation (Harris & Harris 2008). If the lean mindset is not already existing before implementing the process technology, the result may not be lean after the implementation (Liker & Meier 2006), (Zafarzadeh 2013). Further, for the companies to become agile they first must be lean (Ranjan & Kumar 2016).

We know that collaborative robots enable quick response to changing requirements when changed customer demand or change in design of the product (Kruger et al. 2009), (PWC

2014). The author need to study how to create flexibility when focusing on lean. Further, also reveal how the collaborative robots can create lean processes.

## 1.4 Delimitations

To the best of one' knowledge, an in-depth discussion on how collaborative robots fit into established supply chain strategies (i.e. lean, agile, leagile) is lacking from the scientific literature. Because of this, the thesis will mainly be approached as a literature study research. This includes explorative studies of cases provided by the literature accomplished to provide new understanding on a new problem and to generate new ideas and principles that need further research.

## 1.5 Research question

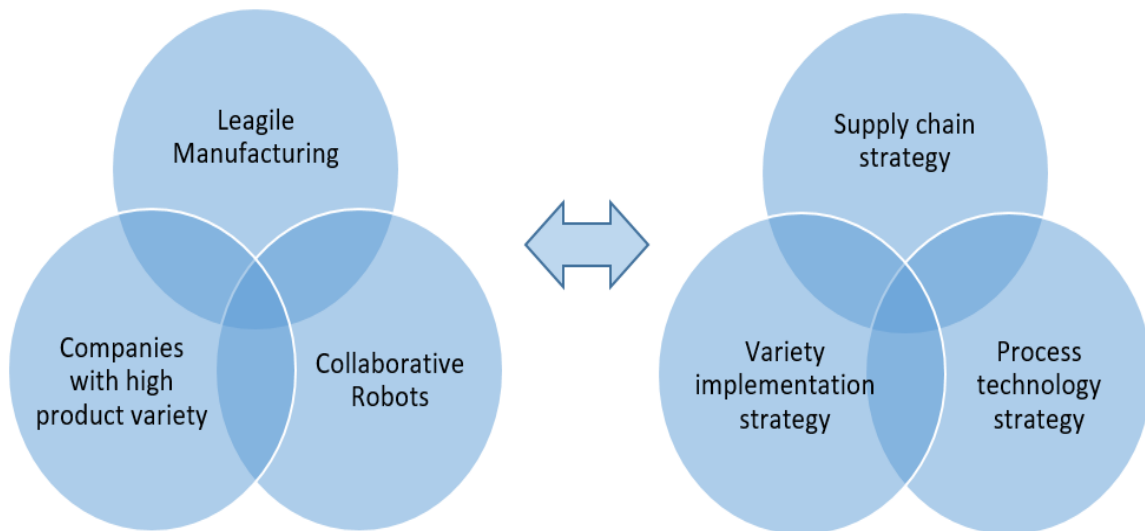
Research question: Collaborative Robots – a process technology strategy to enable Leagile Manufacturing.

Divide the research question into three topics (Figure 1-2) and combine them to seek an appropriate conceptual framework:

- **Collaborative robots:** 1) How collaborative robots can help to create lean processes. 2) How to create flexibility and reconfigurability in the production line when integrating collaborative robots.
- **Leagile manufacturing:** 3) How to create flexibility while focusing on lean.
- **Application:** Companies with rapidly changing market demands.

These three above topics will generate the underlying research questions to be applicable for further research, analysis and final to be answered.

- RQ 1: How collaborative robots can help to create lean processes.
- RQ 2: How to create flexibility and reconfigurability in the production line when integrating collaborative robots.
- RQ 3: How to create flexibility while focusing on lean.



**Figure 1-2. Main topics of the research question.**

## 1.6 Methods to study the problem

The thesis is essentially approached as a literature study research due to the lack of a physical installations, and the explorative case studies is intended to provide new understanding on new problems with limited research and by this generate new principles and ideas that need further research. Triangulating an explorative literature study (by reviewing supply chain management and production systems literature and real-life cases) and semi-structured expert interviews. Further develop a conceptual framework to show optimal configurations between robotic technologies and business systems to apply and generate new understandings on the “Leagile-Cobot” production/process design.

## 2 Literature review

By the literature review searching to find the state of the art for collaborative robots and state of the art for lean-, agile and leagile manufacturing and their strongly connected manufacturing systems. Finally, merging application, leagile manufacturing and collaborative robots together.

### 2.1 Application

Today industrial applications for collaborative robots is commonly found in the subcontractors for the automotive-, pharmaceutical and electronics manufacturer industry. This is industries with generally high variety and dynamically changing market requirements. The automotive industry has traditional been associated with mass production, but in the past decades there have been changes going on in relation to more “mass customization” with demands for higher degree of adaption to individual tastes, opinions and needs from the customers. This have been leading to a higher complexity and many product variants (Scholer et al. 2015).

But many other than the above-mentioned industries can use this hybrid technology (close cooperation between human and robot) due to more flexibility, adaptability and reusability of production systems, and by this reducing the amount of fixed production cost in relation to variable cost (Kruger et al. 2009).

One of the motivation factors for the industry to apply collaborative robots in their manufacturing is the process optimization by the human-robot cooperation. By let the humans do the rewarding and value-added tasks and let the robots do the repetitive and monotonous tasks which is not suitable for humans in an ergonomically manner. By sharing the tasks between human and robot we can increase the efficient, capacity, quality and product variation and at the same time reduce the production cost (Kruger et al. 2009).

### 2.2 Lean Manufacturing

The “Toyota way” field book (Liker & Meier 2006) will be used to define the state of the art in Lean manufacturing of today. All sub chapters except “2.2.7 lean indicators” is based on this book.

State of the art due to lean thinking in a company is all about how to implement a lean mindset into the daily work. To be able to have a lean mindset and perform lean manufacturing it is important to first define the philosophy of the company and begin to live it. Making a social pact with the employees and partners and to maintain the continuity of purpose (Liker & Meier 2006).

### 2.2.1 Minimizing waste.

Lean manufacturing is a systematic method to eliminate waste (Muda). Using less to create more by waste reduction. Cost reduction, shorter lead time, more flexibility, less Work in Process (WIP), less inventory and better environment (Womack et al. 1990). Lean manufacturing take also into account waste due to unevenness work load (Mura), and waste created by overburden (Muri). Lean means eliminating waste, and the success is dependent on three things (Liker & Meier 2006):

- Understanding the concepts which support the lean philosophy.
- Acceptance of all aspects of the lean process.
- Implementation plans containing a systematic, cyclical and continuous eradication of waste.

The eight major wastes identified by Toyota is of type non-value-added activities (Liker & Meier 2006):

- Overproduction (Producing the items too early or in greater amounts than needed)
- Over processing or incorrect processing. (Inefficiently processing, poor quality)
- Excess inventory
- Unnecessary movement. (Reaching for or looking for tools and parts or unnecessary walk distance)
- Waiting. (Waiting for the tools or workstation to be available)
- Transportation or conveyance. (Moving WIP from place to place)
- Unused employee creativity. (Ideas, skills, improvements by not listening or engaging employees)
- Defects. (Waste due to not correct production and rework)

### 2.2.2 Create initial process stability.

Get to basic stability by produce consistent results by producing the same quantity of products, with the same amount of resource time (people and equipment), with high degree of reliability. By developing process stability, we are also creating a foundation for further aspects of lean processes. Some strategies and tools to create stability shows in table 2-1 below:

Strategies	Primary lean tools	Secondary lean tools
<ul style="list-style-type: none"> <li>• Eliminate or reduce variability</li> <li>• Eliminate waste</li> <li>• Improve Operational availability</li> </ul>	<ul style="list-style-type: none"> <li>• Standardized work</li> <li>• Quick change-over</li> <li>• Problem solving</li> </ul>	<ul style="list-style-type: none"> <li>• Data collection and measurements</li> </ul>

**Table 2-1. Some strategies and tools to create stability. Adapted from (Liker & Meier 2006)**

### 2.2.3 Create connected process flow (continuous flow/one-piece flow).

Products that move in the direction of one-piece flow is also called continuous flow. The products then move continuous through the processing with minimum delay and shortest possible distance. Single piece flow is a definition of flow and demands an accurately controlled process under specific environments (Liker & Meier 2006).

When all this processes are connected and a shutdown appear one place in the production, the entirely facility and perhaps across multiple facilities will be shut down if the problems are not corrected effectively. This is unacceptable in many companies, but in Toyota they see it as an opportunity to identify weakness. By this they can fight the weakness and improve the overall system for the long term (Liker & Meier 2006).

There is a relationship between the primary principle of lean, identification and elimination of waste and to reducing batch size to move toward continuous flow. The requirement to eliminating waste is creating flow, and the requirement for the principle of pull is “just in time”. Pull require less inventory and have an acceptable flow factor (Liker & Meier 2006).

We need some basic elements for achieving smooth flow (Liker & Meier 2006):

- Operation cycle time – Due to the takt time to prevent overproduction or waiting time.
- Consistent capability – Due to achieve the requirements to the customer.
- Consistent application and availability of resources – People, material and equipment.
- Reliability of processes and equipment – Simplicity and ease of use.

Table 2-2 below shows some strategies and tools used in creating connected process flow:

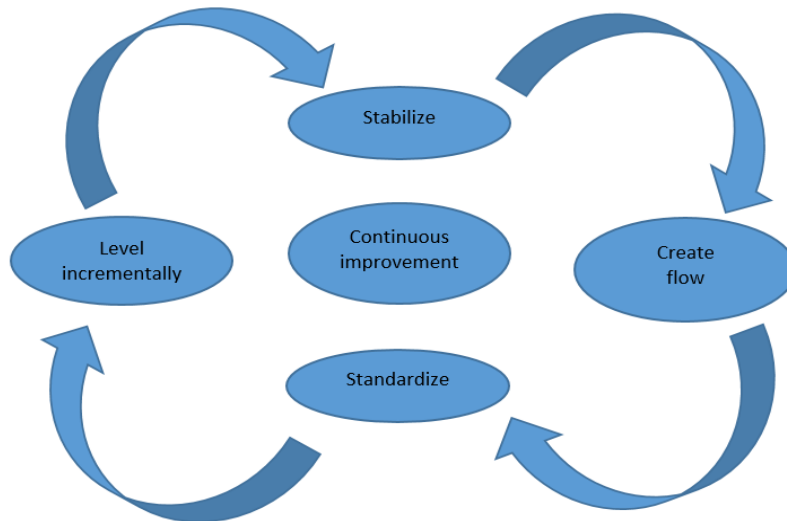
Strategies	Primary lean tools	Secondary lean tools
<ul style="list-style-type: none"> <li>• Establish connected processes</li> <li>• Identify weak links in the flow and make improvements</li> <li>• Continued elimination of waste</li> </ul>	<ul style="list-style-type: none"> <li>• Visual controls</li> <li>• Workplace/cell design</li> <li>• Pull techniques</li> <li>• Clearly defined customer</li> </ul>	<ul style="list-style-type: none"> <li>• Kanban</li> <li>• Problem solving</li> </ul>

**Table 2-2. Some strategies and tools used in creating connected process flow. Adapted from (Liker & Meier 2006).**

#### 2.2.4 Standardized processes and procedures.

By standardize processes and procedures we are creating consistent performance.

Standardizing is a part of the continuous improvements and shows in figure 2-1 below. When the process is stable, we are fitted to start the continuous improvement (Liker & Meier 2006).



**Figure 2-1. Continuous improvement cycle. Adapted from (Liker & Meier 2006)**

Standardization is an ongoing activity, identify the problems, find the methods to use and how to use them.



Standardization is a waste elimination tool and some strategies to establish standardized processes and procedures shows in table 2-3 below (Liker & Meier 2006):

Strategies	Primary lean tools	Secondary lean tools
<ul style="list-style-type: none"> <li>• Develop processes to ensure consistency for all elements of the work</li> <li>• Repeatable work methods that becomes the foundation for kaizen</li> <li>• Establish clearly defined expectations</li> </ul>	<ul style="list-style-type: none"> <li>• Standardized work documents</li> <li>• Production capacity sheet</li> </ul>	<ul style="list-style-type: none"> <li>• Visual controls</li> <li>• Process check sheets</li> <li>• Job instruction training</li> </ul>

**Table 2-3. Some strategies and tools for standardized processes and procedures.**  
**Adapted from** (Liker & Meier 2006)

Quality standards have a natural origin in customer expectations (Liker & Meier 2006).

- General appearance
- Surface quality
- Color matching
- Abnormalities and deformations

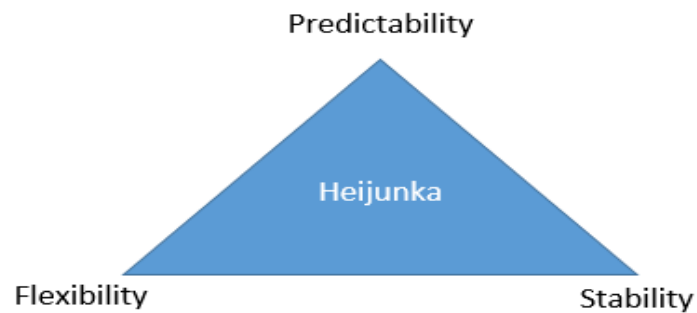
Standard specifications that provide the technical information for producing the product (Liker & Meier 2006).

- Processing methods
- Dimensions and tolerances
- Equipment operation sequences and parameters

Especially visual controls due to standardization is often neglected even though it is the most important part of the standardization. Due to the many different operations and procedures to be handled within every work area, it would be hard to remember all these. Applying visual control leads to make the standards visible, and the operators will get a clear and understandable feedback from the system (Liker & Meier 2006).

### 2.2.5 Leveling.

The art of leveling production is also called “Heijunka” (Figure 2-2). In a lean organization Heijunka is implemented in a later stage than the value streams have been identified and refined. Heijunka is the relationship between stability, flexibility and predictability. Stability by averaging production volume and type over the long term, flexibility by decreasing changeover time and predictability by leveling the demand (Liker & Meier 2006).



**Figure 2-2. Heijunka, adopted from** (Friddle 2014)

### 2.2.6 Technology must fit with the people and lean processes.

Lean manufacturing is well compatible with high-tech technology, but it is not recommended to use technology as a substitute for thinking. It is important to put technology into a proper perspective driven by a practical purpose. “A lean system with technology playing an appropriate role in supporting them.” All new technology must adapt to their systems and philosophy. Tailoring the technology to fit the workers and the company operating philosophy (Liker & Meier 2006):

- How will the technology help to eliminate waste?
- How will technology contribute to the value adding process?
- Will the technology support the workers to do the continuous work in improvement of the process?
- Will the technology support a flexible system that are able to economically adjust when customer demand changing?
- Are the workers using the technology as a “sleeping pillow” instead of thinking about improving the process?
- Do the workers challenging themselves to achieving the goal with the most flexible and least complex technology?
- The technology, people and processes
- Taylor technology
- Technology in perspective

It exists different models for technology adoption from company to company. The main models exist inside the two categories (Liker & Meier 2006):

- Automation
- IT systems for decision making, planning and scheduling

### 2.2.7 Lean indicators and manufacturing strategies.

In the traditional automation process the philosophy is to achieve lower labor cost by let the machines replace the humans on the current operations. In the **lean automation process** the philosophy is that overall waste reduction should be the focus. New technology to be adapted into the overall system and must support the workers doing kaizen and lean processes. The origin simpler and more manual system are already improved and refined due to lean mindset before doing a major technology investment (Zafarzadeh 2013).

(Martinez & Perez 2001) have developed an integrated check list including six categories to assess manufacturing changes towards lean production. The different categories contain selected tasks that describe changes for the manufacturing to become more lean oriented. Table 2-4 below shows this lean indicator checklist.

Category	Definition	change
<b>Elimination of zero value activities</b>	Number of times and distance parts are transported	decrease
	Percentage of common parts in company products	increase
	Value of work in progress in relation to sales	decrease
	Inventory rotation	Increase
	Amount of time needed for time changed	decrease
	Percentage of preventive maintenance over total maintenance	Increase
<b>Continuous improvement</b>	Number of suggestions per employee and year	increase
	Percentage of implemented suggestions	Increase
	Saving and/or benefits from the suggestions	Increase
	Percentage of inspection carried out by production line workers	Increase
	Percentage of defective parts adjusted by production line workers	Increase
	Percentage of time machines are standing due to malfunction	Decrease
	Value of scrap and rework in relation to sales	Decrease
	Number of people dedicated primarily to quality control	decrease
<b>Multifunctional team</b>	Percentage of employees working in teams	increase
	Number and percentage of tasks performed by the teams	Increase
	Percentage of employees rotating tasks within the company	Increase
	Average frequency of task rotation	Increase
	Percentage of team leaders that have been elected by their own team co-workers	Increase
<b>JIT production and delivery</b>	Lead time of customers' orders	decrease
	Percentage of parts delivered just-in-time by the suppliers	increase
	Level of integration between supplier's delivery and the company's production information system	Increase
	Percentage of parts delivered just-in-time between sections in the production line	Increase
	Production and delivery lot sizes	Decrease
<b>Integration of suppliers</b>	Percentage of parts co-designed with suppliers	increase
	Number of suggestions made to suppliers	Increase
	The frequency with which suppliers' technicians visit the company	Increase
	The frequency with which company's suppliers are visited by technicians	Increase
	Percentage of documents interchanged with suppliers through EDI (electronic data interchange) or Intranets	Increase
	Average length contract with the most important suppliers	Increase
	Average number of suppliers in the most important parts	Decrease
<b>Flexible information system</b>	The frequency with which information is given to employees	increase
	Number of informative top management meetings with employees	Increase
	Percentage of procedures which are written recorded in the company	Increase
	Percentage of production equipment that is computer integrated	Increase
	Number of decisions employees may accomplish without supervisory control	increase

**Table 2-4. Lean indicator checklist. Adopted from (Zafarzadeh 2013), (Martinez & Perez 2001).**

## 2.3 Agile Manufacturing

Every business today is in strong competition with its competitors. It is therefore important to produce the products and the specifications customers request with cheaper rates, reliability and delivered at the expected time. This can be possible by adopting a system that gives the ability to allow a rapid response to follow customers and markets continuously changing requirements, and the modified process design to be executed quickly (Ranjan & Kumar 2016).

“Agile manufacturing is the science of a business system that integrates management, technology and workforce, making the system flexible for a manufacturer to switch over the production of one component to another in a cost effective manner.” (Ranjan & Kumar 2016).

Agility manufacturing contains the whole business system from suppliers, distribution services, production facilities and all customers tied together via material feed-forward and information feed-back system (Naylor et al. 1999). This system allows rapid response to customers and the markets continuously changes without expense to decreased quality and increased cost. Before the company can become agile they must be lean in all levels. Without mastering lean manufacturing, they cannot expect to become agile (Ranjan & Kumar 2016).

The factory of tomorrow must be efficient due to rapid changes and flexibility, handle flexibility and safeguard high quality products. The company must ensure both efficiency and quality of a mass production while dealing with a greater complexity in the products. To support this there is a need for dedication, innovation, continuous improvements and use of new supporting technology. By study weakness and strengths in the manufacturing processes and find out where problems occur and where it is lagging. By using agility where the production is lagging, due to being able to provide a rapid response to continuously changing customer requirements. Here is where the company should consider to apply agility and the amount of agility to apply (Ranjan & Kumar 2016).

For the companies to become agile they first must be lean. This manufacturing philosophy was first presented by Toyota and was a drive force for replacing mass production. It is a way of thinking and is a human system approach that creates a culture that supports continuous improvements of production and its processes. In terms of system properties by being customer forced and customer driven, all employees both “in-house” and outside to be customer of their upstream colleagues. By developing a pull system from the customer

through all steps all the way up to the decision makers in the company and gives the company the ability to return better design, quality, service and flexibility to compete with their competitors in the global market. This further accommodate their changes in production processes and their possibility to cope with changes in the requirements without affecting the quality and cost (Ranjan & Kumar 2016).

## 2.4 Leagility – Combining Lean and Agile manufacturing paradigms in the total supply chain

Today's market is becoming more globalized and the global competition is increasing. The products are becoming more complex and the product life cycle is getting shorter. The price focus will continue to be an important factor in deflationary market conditions, but it have also become recognized that agility and responsiveness have become increasingly important in an ever changing marketplace with dynamically changing requirements and high product variety (Christopher et al. 2006).

Leanness is about developing a value stream to eliminate all type of waste and requires a level schedule. Agility is about how to use market knowledge and a virtual corporation to utilize profitable possibilities in a dynamically changing market place. Agile manufacturing is best suited to satisfying a changing production demand in terms of variety and volume (Naylor et al. 1999). According to (Christopher et al. 2006), lean concepts is suitable for relatively stable customer demands and when variety is low. When volatile customer demands and variety is high the Agile concepts is most suitable. Agility is primarily concerned with the responsiveness when unpredictable and turbulent markets, and the keyword for this concept is flexibility.

It is not about Lean vs Agile, but to combine these different concepts into a hybrid system with benefits from both worlds. In many cases there will be a requirement for the Lean-Agile strategy to be brought together in a hybrid “Leagile” solution (Naylor et al. 1999).

The choice of a supply chain strategy has become more and more important because of the global competition, the complexity of the products and the short lifecycle of the products. This strategy should be underpinned by a careful examination of the demand characteristics of the different products and markets served by the company (Christopher et al. 2006). The supply chains consist of a network of different elements as resources, activities and

organizations connected to stimulate the market demands (Varga & Covacs 2016). These different supply chain members contains the material suppliers, distribution services, production facilities and all customers tied together via material feed-forward and information feed-back system (Naylor et al. 1999). When designing supply chain strategies for supporting a high level of variety of products in varied markets it has been increasingly accepted that “one size does not fit all” (Shewchuk 1998).

Today three types of supply chains are described and are applied based on different circumstances (Varga & Covacs 2016):

- Lean supply chain
- Agile supply chain
- Leagile supply chain

Lean supply chain: The main goal in lean organization is to reduce or eliminate different types of waste. Usually in a mass production with high volume and low variety under predictable and stable environments, and it is important to have a long-term trading relationship between the chain members (Varga & Covacs 2016).

Agile supply chain: Agile concept is evolved from the lean concept. Agile supply chain to be flexible and present high responsivity due to the everchanging demands from the market. The relation between the companies and the market is very important to handle unexpected market changes. The different companies in the chain are cooperating due to a virtual enterprise and all the companies must be highly flexible. Important qualities for agile manufacturing as follows (Varga & Covacs 2016):

- Workers with high competence
- Innovative management
- **Flexible and “state of the art” technological solutions**

Leagile supply chain: Leagile is a concept combined of both lean and agile by combining lean advantages due to cost and standardization and agile due to flexibility. Usually applied in “custom-assembled” products because of the customer’s individual needs. Producing higher mix of the products with often lower volume and higher manufacturing cost (Varga & Covacs 2016).

Table 2-5 below shows the distinguishing attributes due to the different supply chains.

Distinguishing attributes	Lean supply chain	Agile supply chain	Leagile supply chain
Market demand	Predictable	Volatile	Volatile and unpredictable
Product variety	Low	High	Medium
Product life cycle	Long	Short	Short
Customer drivers	Cost	Lead-time and availability	Service level
Profit margin	Low	High	Moderate
Dominant costs	Physical cost	Marketability costs	Both
Stock out penalties	Long term contr.	Immediate and volatile	No place for stock out
Purchasing policy	Buy goods	Assign capacity	Vendor managed inventory
Information enrichment	Highly desirable	Obligatory	Essentials
Forecast mechanism	Algorithmic	Consultative	Both/Either
Typical products	Commodities	Fashion goods	Product as per customer demand
Lead time compression	Essential	Essential	Desirable
Eliminate Muda	Essential	Desirable	Arbitrary
Rapid reconfiguration	Desirable	Essential	Essential
Robustness	Arbitrary	Essential	Desirable
Quality	Market qualifier	Market qualifier	Market qualifier
Cost	Market winner	Market qualifier	Market winner
Lead-time	Market qualifier	Market qualifier	Market qualifier
Service level	Market qualifier	Market winner	Market winner

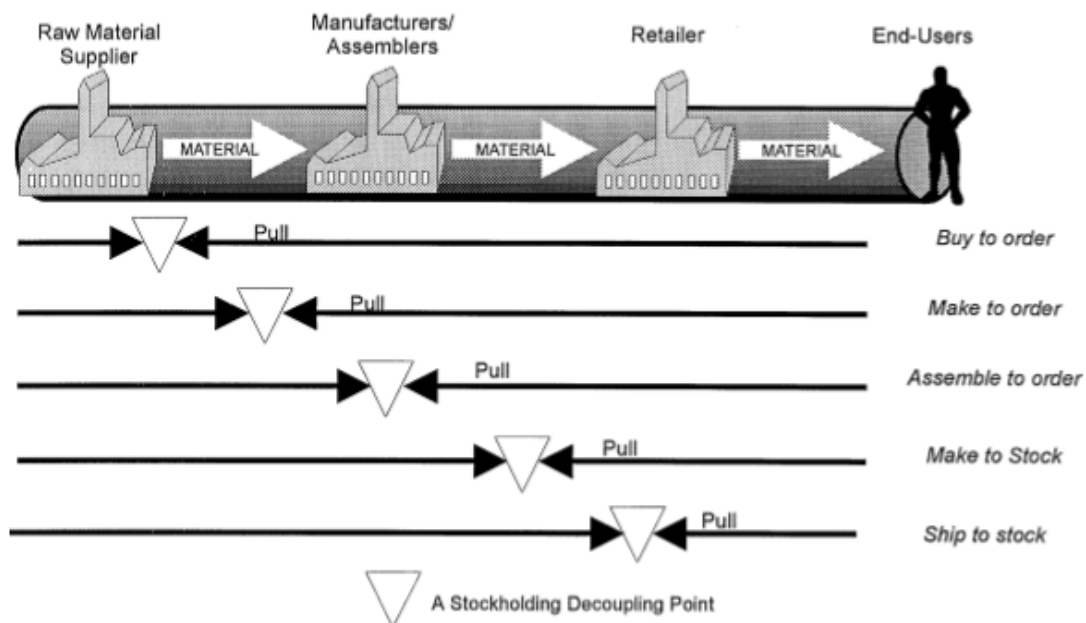
**Table 2-5. Supply chain attributes. Adopted from (Varga & Covacs 2016)**

According to (Christopher et al. 2006) in the journal “A taxonomy for selecting global supply chain strategies” they proposed a taxonomy to guide the selection of appropriate global supply chain strategies. In their work, they claimed that earlier taxonomies were focusing on the nature of the product and its lifecycle. They further suggest to additionally focus on lead time and the demand variability. By further revealing appropriate supply chains and based on this being open to put together a plan with multiply supply chains.

The total supply chain strategy when combining Lean and Agile must consider the market knowledge and the position of the decoupling point (DP). The key difference between Lean and Agile manufacturing paradigm will determine the location of the decoupling point due to meet the customer requirements. This location of the decoupled point is where to place the buffer between dynamically changing customer demands and smooth production. The DP is crucial when considering when to use Lean or Agile manufacturing techniques (Naylor et al. 1999).



The supply chain strategy is considering where the structure and the DP are positioned along the supply chain. This is based on when and where to adopt lean or agile manufacturing. The figure below shows a simplified supply chain structure where the DP is the inventory stock holding point between high variety demands and level production schedule for low variety demands. DP to be positioned between the side of the supply chain which response directly to the customer and the other side which use forward planning. DP is therefore determined based on the longest lead time customer is willing to wait and customer desire for variation of the product. Downstream from DP products are market driven and the customer is pulling. Upstream is a kind of push system driven by forecast using Kanban. In figure 2-3 below we see that it exist different categories of DP positions in the supply chains (Naylor et al. 1999).

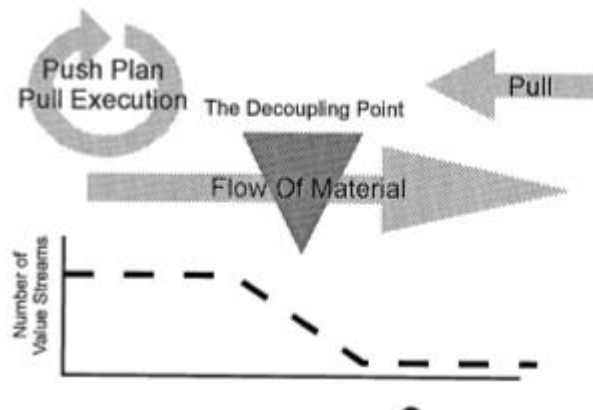


**Figure 2-3. Supply chain strategy.** Adopted from (Naylor et al. 1999).

Different categories of DP positions in the supply chains as follows (Naylor et al. 1999):

- Buy to order: Unique products, different raw material, long lead time, demands for the products is highly variable.
- Make to order: Different products, same raw material, possibility for varied mix, possibility for varied volumes, possibility for varied locations. Long lead time but reduced compared to "buy to order".
- Assemble to order: Customization is postponed to the latest stage. Lead time to be significantly reduced. Final link in the supply chain that supports a certain variety of product mix. Still opportunities for varied locations.
- Make to stock: Standard product, varied locations.
- Ship to stock: Standard product, fixed locations.

The DP effect is visualized in figure 2-4 below and shows the relationship between the characteristics of the lean and agile paradigms.



**Figure 2-4. The DP effect. Adopted from (Naylor et al. 1999).**

Downstream of the DP consist of high product variety with high variable demand. Upstream from the DP the demand is decreased with less product variety. Because of this we know that the point of product differentiation is at the DP or downstream from the DP. At the DP it is desirable to place the stock-buffer between downstream variable demand and upstream level production schedule (Naylor et al. 1999). By using leagility the supply chain goes from a pure lean supply chain to on that incorporate agility from the DP and downstream.

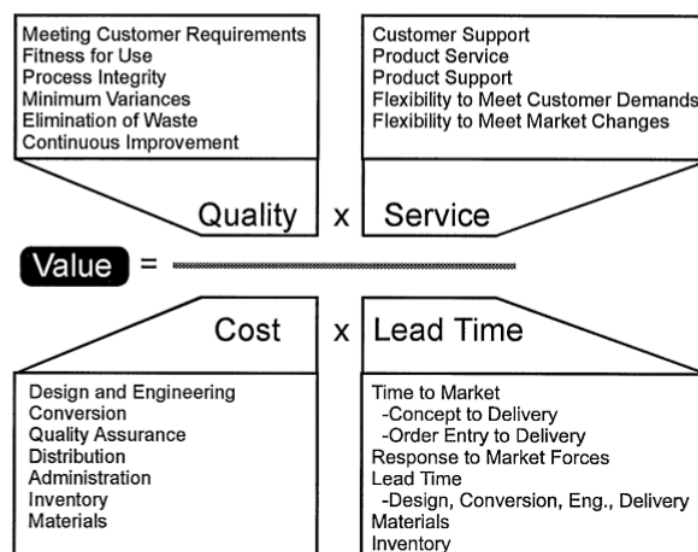
Table 2-6 below shows some key characteristics of Lean and Agile manufacturing paradigms as supply chain strategies. This information is based on both literature study and case studies performed by (Naylor et al. 1999).

Keyword	Lean	Agile
Use of market knowledge	○ ○ ○	○ ○ ○
Virtual corporation/Value stream/ Integrated supply chain	○ ○ ○	○ ○ ○
Lead time compression	○ ○ ○	○ ○ ○
Eliminate muda	○ ○ ○	○ ○
Rapid reconfiguration	○ ○	○ ○ ○
Robustness	○	○ ○ ○
Smooth demand/Level scheduling	○ ○ ○	○

Note: ○ ○ ○ = essential. ○ ○ = desirable. ○ = arbitrary.

**Table 2-6. Rating the importance of different characteristics between leanness and agility. Adopted from (Naylor et al. 1999)**

Agile manufacturing will ensure the production processes to have a quick response due to changing requirements from the market, rapid reconfiguration of the production processes and therefore the possibility to change to a wide range of products. This will increase the flexibility and further shows that Agility focuses on service levels for product differentiation. Agile manufacturing will eliminate as much waste as possible but it is not prerequisite. Lean manufacturing will ensure to eliminate all non-value waste in the production process. Lean manufacturing also will be as flexible as possible but it is not prerequisite (Naylor et al. 1999). Figure 2-5 below shows the total value metric adopted from (Naylor et al. 1999)



**Figure 2-5. Total value metric. Adopted from (Naylor et al. 1999)**

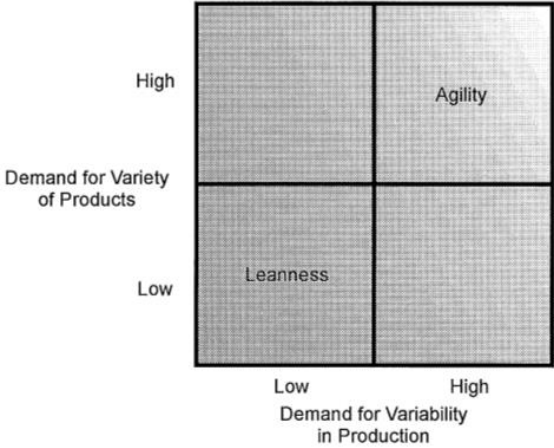
Table 2-7 below shows the benefit of using both Agility and Lean manufacturing paradigms where lean focuses on cost and agile focuses on service level.

Metric	Agile	Lean
Lead time	○ ○ ○	○ ○ ○
Service	○ ○ ○	○ ○
Costs	○ ○	○ ○ ○
Quality	○ ○ ○	○ ○ ○

Note: ○ ○ ○ = key metric. ○ ○ = secondary metric. ○ = arbitrary metric.

**Table 2-7. Rating the importance of the different metrics for Agility and Leanness.**  
 Adopted from (Naylor et al. 1999)

Figure 2-6 below shows the different situations for deciding when and where to adopt lean or Agile manufacturing. As the figure shows, most leanness when both “Demand for variability in production” and “Demand for variety of products” is low. On the other hand, highest degree of agility when both “Demand for variety in production” and “Demand for variety of products” is high.



**Figure 2-6. Applications of leanness and agility.** Adopted from (Naylor et al. 1999)

## 2.5 Manufacturing systems

The different supply chains described in chapter 2.4 above are strongly related to associated manufacturing systems:

- Dedicated Manufacturing System (DMS/DML) → Lean supply chain
- Flexible Manufacturing System (FMS) → Agile supply chain
- Reconfigurable Manufacturing System (RMS) → Leagile supply chain

Dedicated manufacturing line (DML) is often applied when producing a low product mix with high efficiency and volume. Machines applied in these type of manufacturing do not have so much complexity due to their operations. (Varga & Covacs 2016)

Flexible manufacturing systems (FMS) is often applied when producing high product mix with lower volume. Machines applied in these type of manufacturing have more complexity and more variety due to their operations (Varga & Covacs 2016).

Reconfigurable Manufacturing System (RMS) combining the advantages of DML and FMS. RMSs main focus is about flexibility when reconfiguration of the production lines due to changed demands, gives low stock and shorter production time (Varga & Covacs 2016).

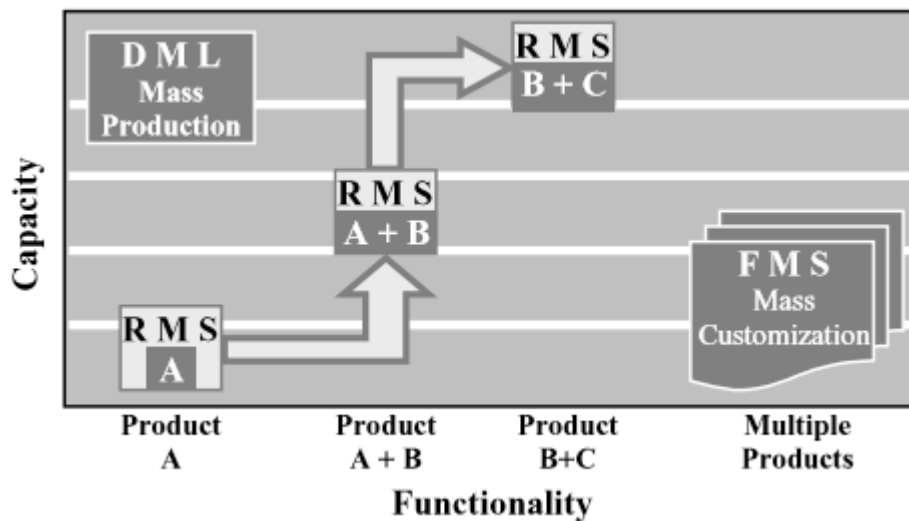
According to (Varga & Covacs 2016), “DML systems are using lean principle, and FMS is closer to agile manufacturing”. The important is to see the relations between the different supply chain concepts and their strongly connected manufacturing systems. Engineers of today has many additional opportunities to adapt the manufacturing systems to the market demands because of the digitalization and all the available tools this progress of digitalization has brought. From these progresses, new systems have been evolved and FMS and RMS are results from these processes. FMS and RMS are better prepared to react to disturbances occurred in the supply chains more rapidly and with higher precisions.

“A manufacturing system transforms raw materials into products” (Bi et al. 2008), and the goal for the company is to achieve profit, reputation and market share. Below is listed some important requirements due to the environments in today’s global competition that has a great impact on the performance of the manufacturing systems (Bi et al. 2008).

- Short lead time: Product lead time can ensure earlier introduction of the product and give advantage over competitors and increase peak sale. Possibility for obtain and retain a bigger share of the market.
- More variants: Customization of the products. May stimulate more customers with different opinions, tastes and needs.
- Low and fluctuating volumes: Today's low and fluctuating volumes is because of global competition, shorter life-cycles of the product, increased quality/durability of the product and fragmentation of the market because of product-customization.

- Low price.

Figure 2-7 below is adopted from (Elmaraghy 2006) and shows the difference between DLM, FMS and RMS due to functionality and capacity. This visualizes the strength of RMS due to its reconfigurable skills. Unlike the other manufacturing systems, RMS have the characteristics of adjustable machine structure, part family system focus and customized flexibility.



**Figure 2-7. Reconfigurable manufacturing systems regarding capacity and functionality. Adopted from (Elmaraghy 2006), (Koren et al. 1999)**

The global and ever changing market demands presents challenges to the industry in terms of obsolescence of the manufacturing systems. Because of this it is important to prolong the life of the manufacturing systems. By doing them easily upgradable and facilitating to the possibility to add/remove new functionality and new technology. RMS are using modular building blocks when designing the system for producing of a part family. FMS on the other hand provide a more general flexibility due to built-in functionality in the manufacturing equipment. “Instead of providing a general flexibility through the use of equipment with built-in high functionality, as in FMSs, RMSs provide customized flexibility through scalability and reconfiguration as needed when needed to meet market requirements” (Elmaraghy 2006), (Mehrabani et al. 2000). Due to capacity and functionality, RMS lie between DML and FMS, but neither capacity or functionality are fixed as they are in DML and FMS (Elmaraghy 2006), (Mehrabani et al. 2000).

“It is seen that the RMS paradigm is one of the most effective paradigms to meet some key requirements such as changes and uncertainties” (Bi et al. 2008). RMS consist of three main design components: Architecture design, configuration design and control design, and aim at (Elmaraghy 2006):

- Reducing lead time for reconfiguration of existing or new systems.
- Rapid system modification, new functionality and technologies by using basic HW and SW modules.

## 2.6 Collaborative robots

Increased global competition causes rapid changes in the market demands. This require more effective business strategies and production systems, and these improvements must be made at all levels in the companies (Ore 2015). This is a driver to take advantage of collaborative robots and simultaneously introducing productivity improvements at all levels in the supply chain.

Market is changing towards customer-specific individual production and shorter cycles for the products. The different product variants are growing and demanded processing time are decreasing (Varga & Covacs 2016), (Ranjan & Kumar 2016), (Bi et al. 2008), (Bernhardt et al. 2007). Because of this the manufacturing systems and equipment applied must be flexible due to the changing customer demands.

Collaborative robots give a closer physical collaboration with a shared workspace between robots and humans collaborating towards a common goal. By this collaborative robots support the humans using their skills to perform value-added tasks more efficiency when robots perform repetitively and monotonous tasks with high precision, speed and endurance. (Ore 2015), (Kruger et al. 2009). The simple tasks suited for robots to be found upstream in the line, and the varied complex tasks belonging to the customization is found downstream performed by the human operators. (Kruger et al. 2009). A widespread way to share tasks between robot and human is using sequential division of labor. By sharing the tasks between human and robot we can increase the efficient, capacity, quality and product variation and at the same time reduce the production cost (Kruger et al. 2009), and it is important to find the right balance and the right type of automation (Harris & Harris 2008).

Collaborating robot systems can be divided into two groups where both robot and human are working in the same workspace (Kruger et al. 2009), (Bernhardt et al. 2007):

- Workplace sharing systems (Figure 2-8).
- Workplace and time sharing systems (Figure 2-9).

In workplace sharing systems human and robot do separate tasks in the same workspace. This to be in accordance to the workload leveling. The configuration may be:

- Robot performing a handling task and operator performing an assembly task.  
OR
- Robot performing an assembly task and operator performing a handling task.



**Figure 2-8. Time distribution between human and robot in workplace sharing system.**  
Adopted from (Kruger et al. 2009).

In workplace and time sharing systems human and robot share work on the same tasks in the same workspace. In addition to avoiding collision with the human, the robot also has to interact with the human to perform the shared tasks (Schraft et al. 2005). The configuration may be:

- Robot performing a handling task and operator performing an assembly task.  
OR
- Robot performing an assembly task and operator performing a handling task.  
OR
- Robot and operator performing an assembly task.  
OR
- Robot and operator performing a handling task.





**Figure 2-9. Time distribution between human and robot in workplace and time sharing system. Adopted from (Kruger et al. 2009).**

The collaboration between robot and human in the same physical workspace require a safety system, and to develop such systems we need some regulations to take into consideration. The international standard “ISO 10218: Robots for industrial environments – Safety requirements” forms the basis for safety in a robot cell. This standard will provide regulations for the human-robot corporation (Oberer et al. 2007). Both technology and regulations related to this field has evolved a lot in the recent years, and much has been done to produce cobots which are adapted to these rules and regulations (Faber et al. 2015):

- Light-weight with restricted action force
- Advanced control technology to avoid collision with humans
- Capacitive shells for the cobots
- Cameras in certain cases

Today’s light weight collaborative robots are easy to move between different locations in the plant, and easy to reconfigure when change of customer demand, and are an excellent example of how we can use collaborative robots in much larger scale with several advantages (Kruger et al. 2009):

- Cost reduction due to the combined strengths of human and robot.
- Improvements of the ergonomics situation for humans.
- Availability and flexibility due to where to install.
- Parallel task operation between human robot to increase efficiency.

Figure 2-10 below shows a UR10 robot from Universal Robots with six articulation points and a wide scope of flexibility. The robot is designed to mimic the motion and range of a human arm.

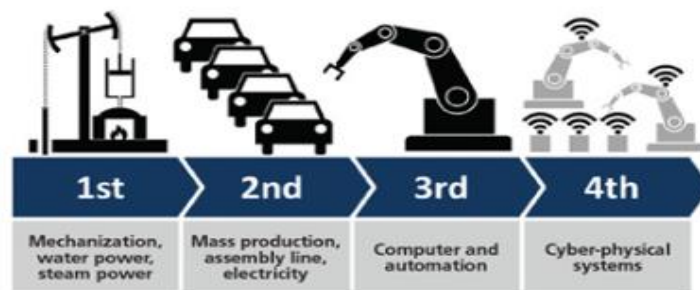


**Figure 2-10. Picture from laboratory in NTNU, Aalesund.**

By introducing a cloud-based architecture on a common platform supporting smart devices we will achieve a more modular and re-configurable production framework, and robots, sensors and other equipment are communicating with each other and exchange data (Bergweiler 2016). Logging of uptime and capacity utilization allows the factory manager to quickly view the results for a specified machine or the whole factory and adjust as needed.

*“With the correct information and reporting, manufacturing companies can improve interactions with their customers, improve quality, improve efficiency, reduce maintenance and reduce inventory. The technology is constantly evolving to meet these requirements more efficiently”. Jodi Romanowski referred to in (Waurzyniak 2015).*

Hyperconnected automation systems are one of the important main-part of the so-called “Industry 4.0” revolution (Figure 2-11) (Reuter 2016).



**Figure 2-11. Showing the “Industrial revolution 4.0”. Adopted from (Roser 2015).**

## 2.7 Theoretical synthesis for collaborative robots in a leagile manufacturing

“Collaborative robots in a leagile manufacturing” is a topic that the author did not find anything precise information about in the literature. Leagile is a concept usually applied when the customers have different individual needs and the products is characterized as “custom-assembled” and where the forecast of the demands are pretty accurate. By combining both lean (cost and standardization) and agile (high variety/flexibility) to producing higher mix of the products with often lower volumes and higher manufacturing cost (Varga & Covacs 2016).

We first need to define the product family and by this each of the components to produce due to find the intersection between lean and agile using the decoupling point. Standard parts have a stable demand and is forecast driven by the lean approach while customized parts are order driven by the agile approach. Based on these characteristics it is possible to plan which type of process technology that is suitable for producing the product consisting of these different types of parts.

The choice of a supply chain strategy should be supported by a careful examination of the demand characteristics of the markets served by the company and the different products produced (Christopher et al. 2006). When changed production demand in terms of variety and volume, agile manufacturing is the preferred choice (Naylor et al. 1999). When production demand is relatively stable and the variety is low, lean concepts are suitable (Christopher et al. 2006), (Christopher 2000).

This supply chain strategy assesses where the structure and inventory stock holding point (DP) is located, and where and when to adopt lean manufacturing for low variety demands and agile manufacturing for high variety demands. By using leagility, the supply chain goes from a pure lean supply chain to on that incorporate agility from the inventory stock holding point and downstream. (Naylor et al. 1999).

When the global market competition is increasing, the products are becoming more complex and the product life-cycle is getting shorter. (Christopher et al. 2006). This global and alteration market presents challenges to the industry in terms of obsolescence of the manufacturing systems. Because of this it is important to prolong the life of the manufacturing systems. By doing them easily upgradable and facilitating to the possibility to add and remove new functionality (Elmaraghy 2006).

Leagile supply chain is strongly connected to the reconfigurable manufacturing system (RMS), and the RMS combining the advantages of both dedicated manufacturing lines (DML) and flexible manufacturing systems (FMS). The RMS focus is flexibility with low stock and short production time when reconfiguration of production lines when changed demands (Varga & Covacs 2016).

According to the author, the above statements are important aspects to consider when choosing the type of process technology to apply (collaborative robots, traditional industrial robots or a combination of these).

Collaborative robots have a quick response to changing requirements and an ability to reconfiguration of the production line with low set up cost and low time consume, proved by explorative case studies (Scott Fetzer 4.1.1), (Continental Auto 4.1.3), (Cooperation human-robot 4.1.5) and in literature (Kruger et al. 2009), (PWC 2014).

The theoretical synthesis is based by the following: (i) applying collaborative robots to manufacturing the customized (non-standard) high variety parts; (ii) applying agile manufacturing principles for the customized (non-standard) parts because agile systems support flexibility by handling rapid changes; (iii) applying lean manufacturing principles in combination with Cobots or industrial robots. Traditionally, fixed automation (industrial robots) are today the most widespread choice because of the cost efficiency (high speed in production), but despite this, cobots are also well suited for use in a lean environment because of their proven ability to make lean processes in addition to their abilities due to rapid reconfiguration.

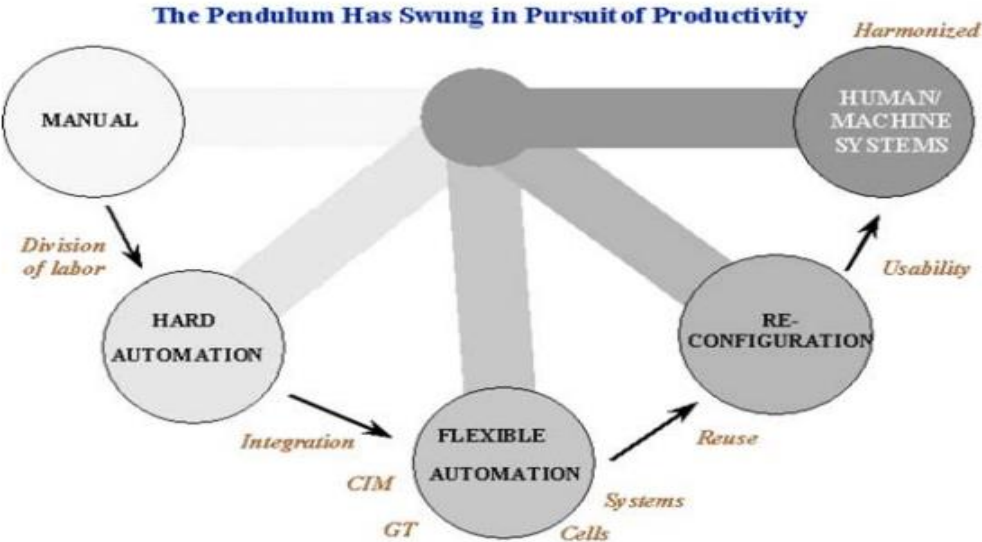
This extrapolation of lean for the standard parts manufacturing and agile for the customized parts manufacturing into leagile manufacturing is done by applying the decoupling point concept to separate between the share of customer demand that can be predicted and the share that is prone to high variability.

Collaborative robots are light weighted, small and easy to move, easy installation because of embedded safety (no need for cages/fences) and easy and intuitive to program by the “follow guiding function”. In addition to the above characteristics, collaborative robots by nature consist of both a robot-part and a human-part, and this is a major advantage due to both flexibility and adaptability, but also an advantage to cost.

By sharing the tasks between human and robot we can increase the efficient, capacity, quality and product variation and at the same time reduce the production cost (Kruger et al. 2009).

The human factor plays an important role together with the automation in the evolution of manufacturing systems. The involvement of humans in the planning of manufacturing systems is crucial to success and competitiveness. “Human operators are probably the most flexible component of a manufacturing system (Elmaraghy 2006). “This presents new challenges in the design, operation, and control of manufacturing systems that go beyond simply good ergonomics, safety, and usability issues” (Elmaraghy 2006), (Yamada 2000), (Yamada & Vink 2000).

Figure 2-12 below shows how the system development has changed to maximize the productive relationship between human and machine over time.



**Figure 2-12. Role of human and automation pendulum. Adopted from (Elmaraghy 2006), (ElMaraghy 2000), (ElMaraghy 2005).**

### 3 Methodological approach

The methodology describes the broad philosophy, underpinning the chosen research methods”. The methodology to backing up all the choices that have been made and link it back to the literature on a clear academically manner, and grouping together research techniques to make a coherent picture (Skillsyouneed 2017).

According to research design this thesis will include both practical and theoretical approaches. The practical research study of this thesis will apply semi-structured interviews of experts in the field of the thesis’ main topics. The theoretical part of this thesis will use the literature and second hand data as a foundation. The literature consists of different papers, articles and journals about robotics, different manufacturing business systems and some cyber physical systems. Second hand data is partly collected by explorative case studies. These explorative case studies include topics about how to apply collaborative robots in manufacturing systems focused on rapidly changing production processes. Showing both how collaborative robots can support lean processes and brings out examples on how they create flexibility into the production. This enables the author to develop new understanding on emerging problems from enabling technologies, and to generate new ideas and principles that need further research.

The research approach is described in the following sections, and it consists of the theoretical approach and methodological approach. The theoretical approach is developed in section 2.7 (theoretical synthesis). This provides the background and motivation to the methodological approach as described in the following sections.

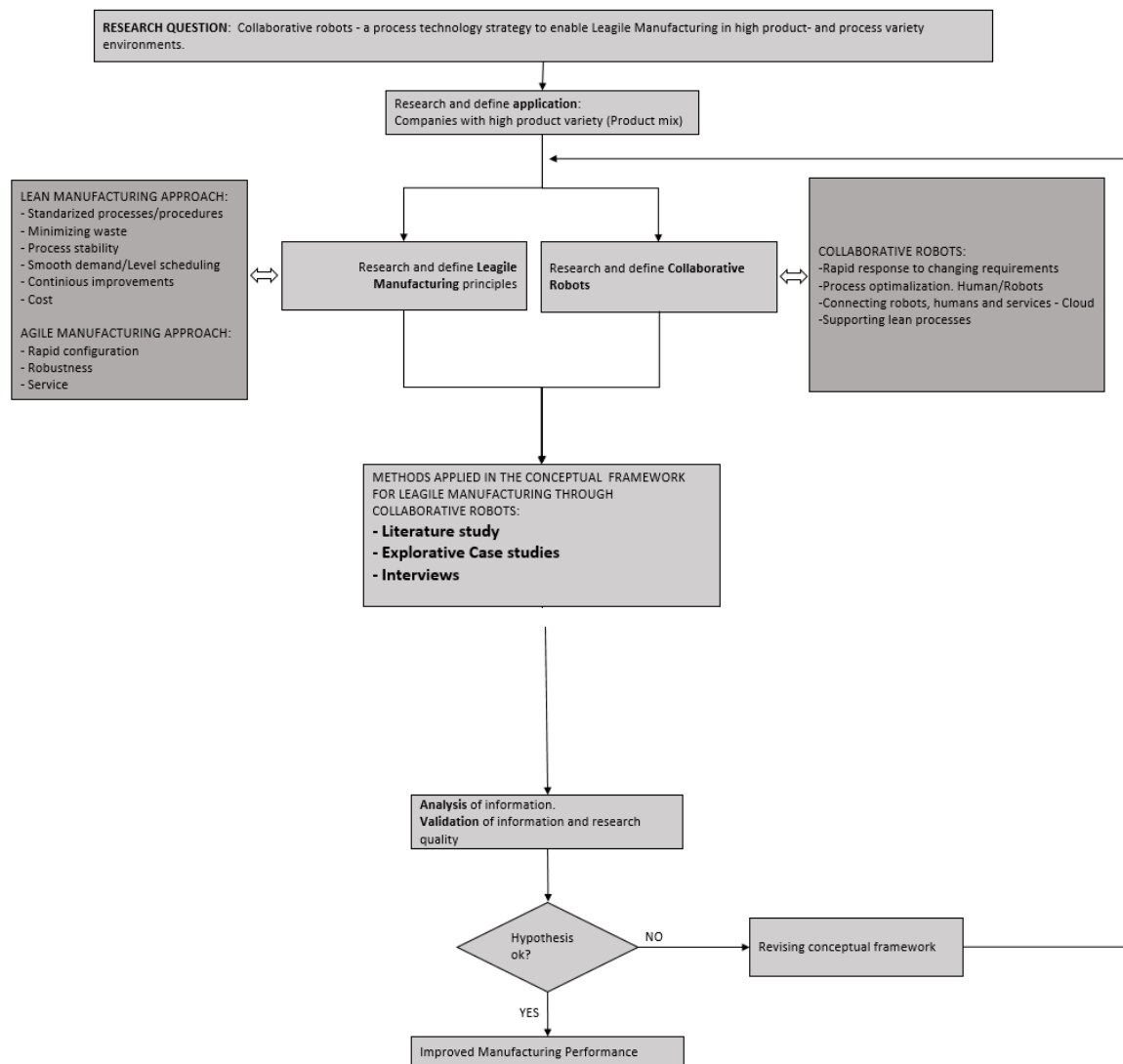
#### 3.1 Research method

In this thesis, an exploratory research will be conducted. This type of research does not usually provide conclusive evidence, but intends to explore the research question by outline the problem better. Unlike a conclusive research which output is a concluding answer of the research questions, the exploratory research contributes to a better understanding of the problem with varying levels of depth without necessarily providing the final answers. When conducting an exploratory research, the researcher must be prepared to change direction due to new data and insight throughout the research period. Exploratory research is particular useful in exploring new issues not explored before (research-methodology.net 2017). In this case, cobots within a leagile systems, and by this forms the basis of more conclusive researches.

A triangulation between the different methods applied such as literature study, interviews and explorative case studies will be performed. The author expects the exploratory research to result in a range of causes and alternative options of solutions for the research questions of the thesis.

In relation to combining collaborative robots and leagile manufacturing there are several possible combinations and ways to put this together in a good function system. Because of this, the author finds it difficult to find a direct and conclusive answers to current research questions. The author therefore finds it appropriate to use an exploratory approach. Study how different parties employ different solutions, by using exploratory case studies and triangulate with already established theory and supplement with interviews of experts to generate a new conceptual framework.

Figure 3-1 below shows a flowchart of the research methodology to visualize the steps in the process of developing the conceptual framework of collaborative robots in a Leagile Manufacturing environment.



**Figure 3-1. Flowchart of the research methodology.**

Advantages of this type of exploratory approach is primarily flexibility and adaptability to change during the research. Exploratory research can potentially save a lot of resources considering which researches are worth pursuing at the earlier stages and further also add a good foundation for further studies in the subject (research-methodology.net 2017).

Disadvantages of this type of approach is the fact that there is generated less amounts of samples/data that may not sufficiently represent the target population. For this reason, it is important for the author to supplement the most potential explorative case studies and sufficient number of real examples. Because of the nature of explorative research, it



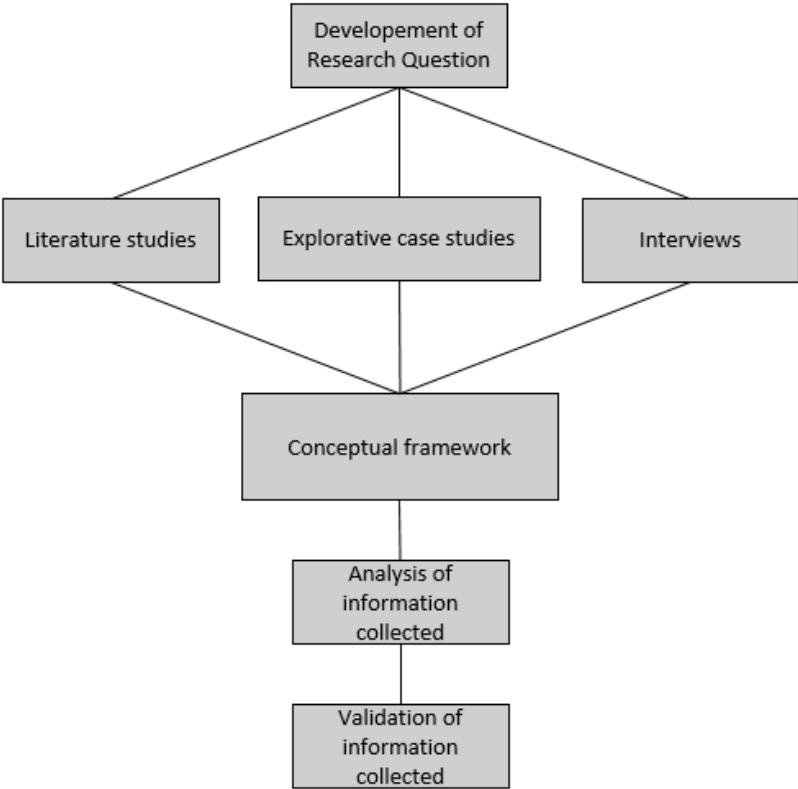
generating qualitative information. It is therefore important to handle the interpretation of such type of information with caution in subject to bias (research-methodology.net 2017).

### 3.2 Research process

The research process consists of following stages:

- Development of Research Question.
- Literature studies for the different topics included in the Research Question.
- Exploratory case studies.
- Interviews of experts in the field of the corresponding topics (Robotics, Lean- and agile manufacturing).
- Triangulating the findings from the different methods applied.
- Research and define each of the corresponding topics: application, collaborative robots and leagile manufacturing.
- Research and define the combined conceptual framework: collaborative robots in a leagile manufacturing in companies with high product- and process variety.
- Analysis of collected information.
- Validation of collected information.

Work process flow chart shows in figure 3-2 below.



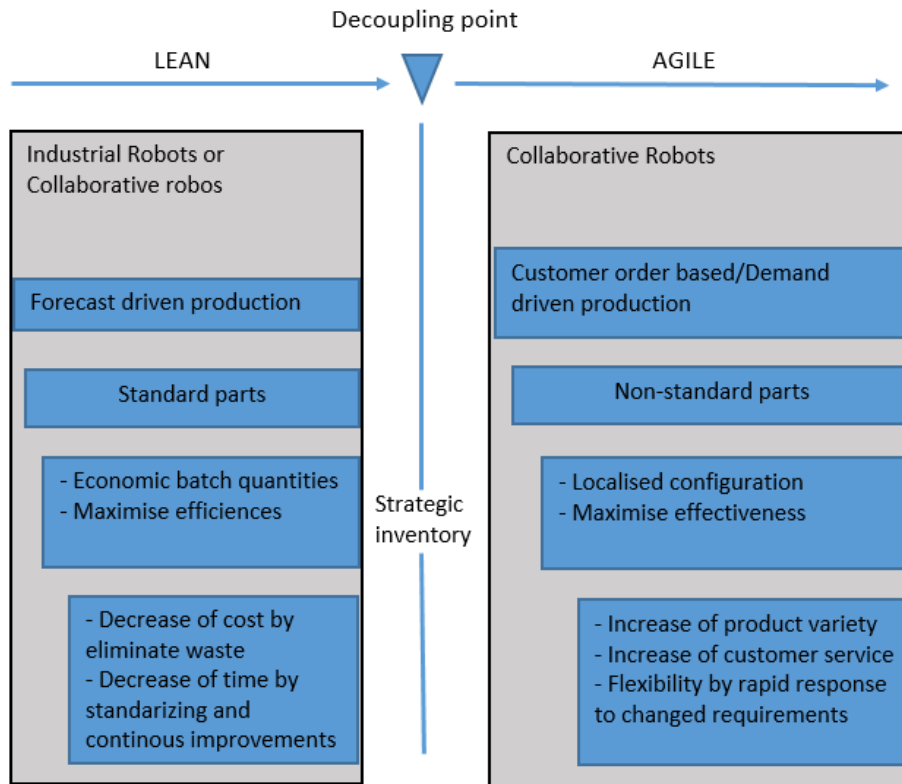
**Figure 3-2. Work process flow chart.**

By using the work process flowchart in figure 3-2 and the flowchart of the research methodology in figure 3-1, developing a conceptual framework of combining collaborative robots within a leagile manufacturing to improve the industrial performance for companies with high product- and process variety. By this provide high variety products with short delivery time due to dynamically changing customer requirements in today's global market. We know that collaborative robots can contribute since it has a rapid response to changing requirements (Kruger et al. 2009). Further the author want to study how to create flexibility when focusing on lean.

In the flowchart (Figure 3-1) above in the research method chapter we combine the leagile manufacturing principles (Manufacturing business system) with the collaborative robots (process technology). The product of this gives us the conceptual framework of “collaborative robots in an leagile manufacturing”.

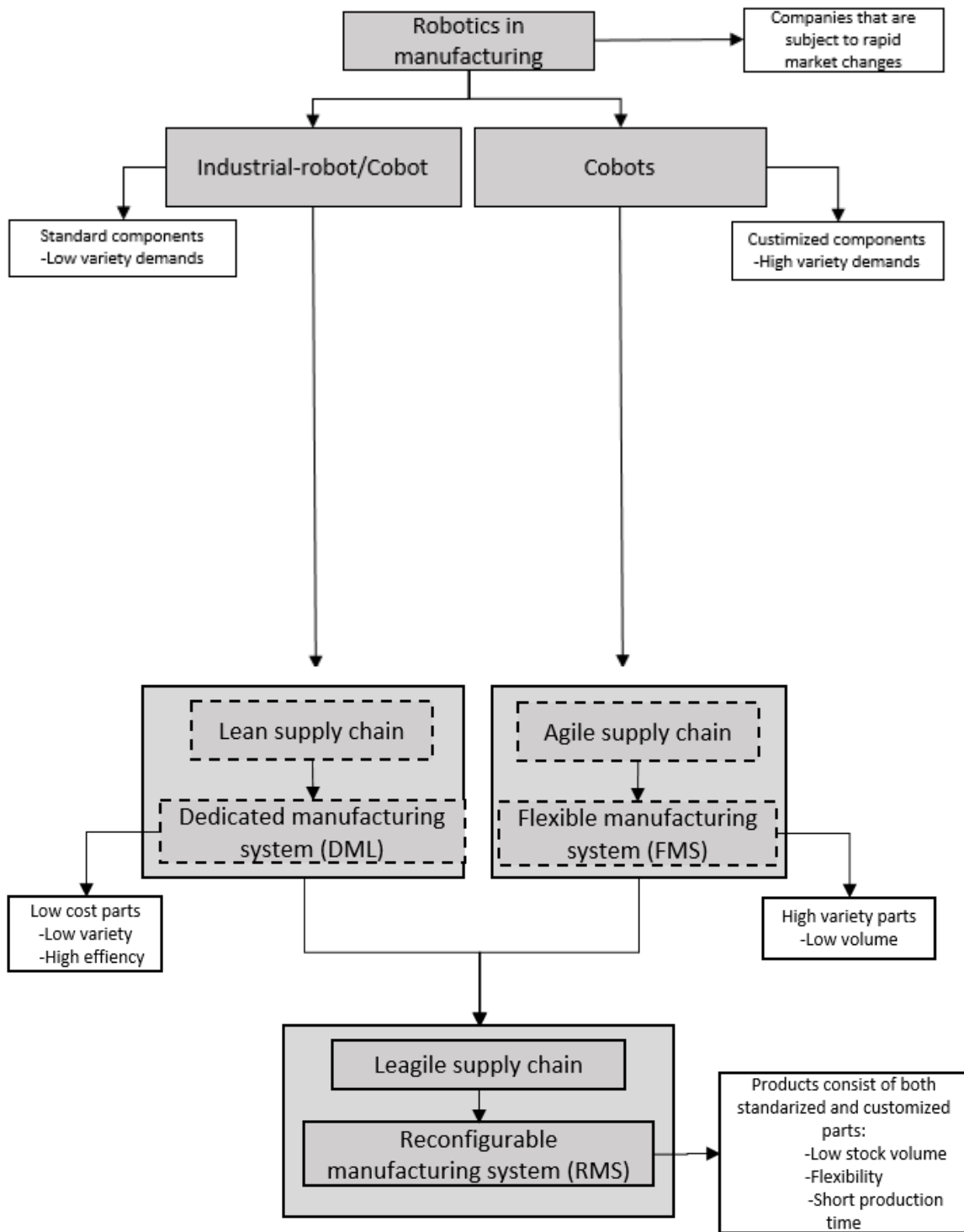
It is well established in the literature (Ulrich et al. 1998);(Kamalini 2001) that “variety creation” and “variety implementation” decisions, together, determine the firm's responsiveness to demand- and process uncertainty. These variety decisions focus on HOW to create variety in the product line, and HOW to implement this across the supply chain. Variety management presents challenges at both strategic and tactical levels where the strategic decisions involve creating an effective variety delivery system. It is **HOW to implement the variety** that is the focus of the author, and within this, the more narrowed strategic area of **process technology**.

Figure 3-3 below shows the process technology strategy and the product process for Leagile manufacturing using both lean- and agile manufacturing principles. This product process is visualized to show how different process technologies are capable to satisfying the different lean- and agile approaches.



**Figure 3-3. Process technology strategy and the product process, Leagile Manufacturing. Adapted from Naylor’s theory on leagility.**

To deliver high product-mix with short delivery time, it is also required to enable a flexible/reconfigurable production line. Figure 3-4 below shows how a leagile system may be achieved through a Reconfigurable Manufacturing System. This enables achieving benefits from both Dedicated Manufacturing Systems, with focus on costs, and Flexible Manufacturing Systems with focus on service level (quickly deliver high variety) (Varga & Covacs 2016).



**Figure 3-4. Combining of flexible- and dedicated manufacturing system.**

### 3.3 Data collection

Data collection methods can be divided into two main categories. Quantitative (Numerical) and qualitative (Non-numerical) data collection methods. When combining quantitative and qualitative data collection methods we get “Mixed data collection method”. (Jalil 2013)

In this thesis, qualitative data collection methods are applied. Qualitative data consist of non-numerical data and describes problems, behaviors, attitudes, opinions, experience and beliefs. Qualitative data often originates from open ended questionnaires, key informant interviews, focus group discussions, field notes or personal log or journals. Primarily object of this type of method is when in-depth information is required or when sample size is not an issue. (Jalil 2013)

The author applies in this thesis explorative case studies to collecting new understanding on new problems and to generate new ideas and principles that need further research. Interviews to collecting quotations about people’s personal perspectives and lived experiences. Further to perform literature studies on existing solutions, suggestions from other researchers and to experience how other industry players solve similar problems.

#### 3.3.1 Data collection methods

Data collection methods in this thesis are as follows:

- Literature studies
- Explorative case studies
- Interviews

#### 3.3.2 Interviews

Interviews is one of the tools for data gathering, and the use of interviews can support the researcher to get valid and reliable data to the research questions and objectives and is a powerful method when collecting in-depth and detailed qualitative data. Data to be further analyzed through content analysis with narrations and quotations (Feroogh et al. 2008). There are in general three types of interviews:

- Structured interviews
- Semi-structured interviews
- Unstructured interviews

Table 3-1 below shows the three different types of interviews.

Interview type	Description
Structured interviews	Structured interview has a rigorous set of questions which not are allowed to be diverted.
Semi-structured interviews	The semi-structured interviews are open and allowing new ideas to be brought up during the interview. Combine the advantage of totally structured and unstructured interviews.
Unstructured interviews	Unstructured interview does not allow the questions to be prearranged. Unstructured interviews are informal and used to explore in depth a general area in which are interested.

**Table 3-1. Three different types of interview. Adapted from (Zhang & Wildemuth 2005)**

In this thesis, a semi-structured interview is applied. This “non-standardized” type of interview and is often referred to as “qualitative research interview”. Combining the strengths from both structured and unstructured interviews by having both flexibility and some degree of standard (Zhang & Wildemuth 2005). The researcher of this thesis has a list of themes and questions to be covered and this will vary between the different interviews within the various subject areas.

### 3.3.3 Secondary data

When performing the research, secondary data was used. This method consists of applying data from other researchers. Also by using explorative case studies, secondary research such as reviewing available literature was conducted.

During gathering secondary data, the author was using different search engines as “Google scholar”, “Oria database” and “Science direct database”. Using search words as “Cobot”, “HRC”, “Collaborative AND Robot AND Human”, “Leagile AND Cobot AND RMS” in

different combinations was applied. Documents due to the information-search was arranged in degree of interest and some methods for excluding duplicated documents and information was applied.

### 3.3.4 Explorative case studies

The author has applied explorative case studies as a method to provide new understanding on a new problem to generate new principles and ideas for developing a concept that need further research (research-methodology.net 2017). The information collected from these case studies will view “the red thread” through these different cases. Especial to show which process technologies that have been applied, how it is used and further in which environment they most often are used.

## 3.4 Analysis of data

The thesis is based on a conceptual framework of collaborative robots in a leagile manufacturing environment. During explorative case studies of high product mix companies, the author will perform a comparison between these explorative case studies to find similarities and to find the common “red thread”. Further analysis of the literature studies and interviews of experts in the field. By these analyses to be able to prove a flexible and adaptable manufacturing performance. All findings from the different methods to be triangulated.

- Analysis from literature study.
- Analysis from interviews of experts of the areas that is associated with the research questions.
- Analysis from explorative case studies.

Qualitative data is gathered from the above-mentioned literature studies, explorative case studies and due to interviews about collaborative robots, traditional industrial robots (fixed automation), lean- and agile and the connected manufacturing systems applied.

## 3.5 Reliability and validity

### 3.5.1 Reliability

According to (Jalil 2013) reliability is to which degree the research can yield consistent results without errors, and a reliable test would give same results every time. Reliability can further be divided into reliability in quantitative- and qualitative methods. Because of this

thesis is based on qualitative research one cannot have comparable measure of reliability, but because of all the explorative case studies shows commonalities this suggest that the reliability is good. During the implementation of the research the author of this thesis has placed great emphasis on using credible sources. In terms of search-engines and choices of databases to use, the author has tried largely utilizing traditional and recognized channels to collect data, such as Google scholar and Oria university database. This concept is a product of literature, explorative case studies and interviews of experts in the fields, and by triangulate the data through these different methods the reliability will increase.

### 3.5.2 Validity

According to (Jalil 2013), gaining the same results several times gives a reliable test, but it is not enough that a measure is reliable if it is not also valid. The results should also be correct. Because of the research problem is concerned with high mix-low volumes companies, the validity is not necessary applicable to other types of companies (Internal validity). To approach the problem in the research, the author applied methods as explorative case studies, literature studies and interviews to collect data for dealing with the problems in the research question. Validity is about how relevant is this approach to the problem. Below is listed some arguments due to defend the validity of the different methods applied in the thesis:

- Explorative case studies: The author tried to highlight the “red thread” in the different studies due to show which businesses collaborative robots are widely used. They also show collaborative robots supports the flexibility the companies need in the production and how collaborative robots can create lean processes. Also by these studies the author wanted to acquire new knowledge and further being able to generate new ideas and principles regarding the current topics/concept.
- Interviews: By this qualitative method the author performed semi structured interviews of experts in the different topics belonging to the research question/problem. Due to validity, choose the right topics and set the framework for this. Further select the questions with care so that they approach the issues. Triangulate the findings from the interviews with the literature studies and the explorative case studies.
- Literature studies: Set the framework for what to be studied and collect knowledge and qualitative data regarding the research problem.

### 3.5.3 Degree of evidence

Degree of evidence is a set of principles which allows the researcher to gauge the rigor of research and rigor is determined by the extent to which the research obeys to the following principles (Jalil 2013):



- Triangulation: Apply mixed method research design by triangulate literature studies, explorative case studies and interviews. This results in multiple sources of evidence to ensure the measurements to become more credible.
- Methodological transparency: To ensure the transparency; literature study, interviews and explorative case studies are traceable and well documented by linking the results from the different methods up to the research question in an orderly and transparent manner.
- Methodological appropriates: By choosing correct research methodology to answer the research question. Per the author of this thesis there is a lack of information of how to combine collaborative robots in a leagile environment in today's literature. This is the background for the author to argue that explorative case studies are a suitable choice of method. This to acquire new knowledge, generate new ideas and principles and suggest a new concept to further study. Interview as a method is also appropriate in this thesis because of the chosen semi-structured interviews are open and allowing new ideas to be brought up during the interview.
- Methodological validity: Internal validity is the focus because of this research includes mainly companies that are segmented within markets which requires high product and process variety, and companies beyond this scope is not including in this validity.
- Sound data collection methods: According to "good practice": Ensure the appropriate use of the data collection methods.

## 4 Explorative Case studies

The author has chosen an explorative study to provide new understanding on a new problem with limited research to generate new principles and ideas that need further research.

### 4.1 Case examples

Based on text-sources and video-sources in relevance with the following cases, and triangulating to achieve the most accurate representation of the truth/reality to generate new concepts. Following case studies presenting several companies using collaborative robots as a process technology strategy in their production.

#### 4.1.1 Scott Fetzer Electrical Group (SFEG). - A high mix–low volume electronics manufacturer in a constantly changing environment.

Scott Fetzer Electrical Group is a high mix–low volume electronics manufacturer from Tennessee, USA which has adopted collaborative robots (cobots) to solve ever-changing tasks in their production lines. The cobots have taken over monotonous and potentially hazardous tasks from the workers. The production has due to Rob Goldiez, General Manager at SFEG been optimized by 20 percent. By reallocating humans and let the cobots take over such tasks the human workers are now performing more rewarding and value-added tasks. By that means being used where the company has seen growth or possibility to fill gaps due to natural attrition (Universal Robots 2016c), (Modern Applications News 2016).

Rob Goldiez Scott have experienced that if they implement one cobot then one employee can be released to another area of the business, and this makes SFEG more flexible as a manufacturer (Modern Applications News 2016).

The cobots at SFEG is a mobile and flexible cobot fleet. These cobots works in practice as a mobile cobot colleague on rolling carts that are easy to transport between different work tasks. This ensuring increased productivity and improve worker's safety. Figure 4-1 below shows a mobile UR10 cobot being deployed at a stamping machine in SFEG's sheet metal department.



**Figure 4-1. The mobile UR10 robot being deployed at a stamping machine in SFEG's sheet metal department. (Modern Applications News 2016)**

Matt Bush, Director of Operations at SFEG is responsible to make SFEG more competitive on the global scale and are always searching for new methods to efficiently automate the factory.

According to Matt, one of the biggest challenges was that SFEG is a high mix – low volume producer and most of their lines don't run every day, so finding ways to put robots on the line was a big challenge. The solution for SFEG was flexibility and adaptability: Re-deployable collaborative robots with embedded safety and no need for safety fences or other surrounding safety equipment as sensors makes the transfer of robots or robot cells around the factory floor much easier. This give also the possibility for workers to work next to the cobots. By moving these cobots around where the needs are it is possible to taking more advantage of existing machinery (Modern Applications News 2016).

Matt claims the cobots of today have the speed and precision of a standard industrial robot, with the ability to work around it with humans. He is always searching for tasks in their processes which are monotonous, labor intensive or potential hazardous.

One of the operations SFEG has automated due to monotonously and repetitively tasks is an operation where workers manually was cutting 16000 wires daily. Figure 4-2 below shows this operation is replaced by a cobot to eliminate monotonously work and the risk of carpal tunnel syndrome (Universal Robots 2016c), (Modern Applications News 2016).



**Figure 4-2. UR 5 robot cutting 16000 wires per day. Eliminating the risk of workers to getting carpal tunnel syndrome. (Modern Applications News 2016)**

Another tasks SFEG have automated is due to safety. Applying mobile cobots to filling epoxy into circuit boards (Figure 4-3). These cobots is part of the SFEG's mobile cobot fleet and at the start of the shift the worker places the cobot into the line and activate it for work (Modern Applications News 2016; Universal Robots 2016c).

Before the cobots entry in SFEG, the employees were making batches of circuits boards manually and send them down the curing line. Today the cobots performs this continuous and provides a one-piece flow (Modern Applications News 2016; Universal Robots 2016c)



**Figure 4-3. Cobot filling epoxy into circuit boards and reduces the risk to human health. (Modern Applications News 2016)**

Rob Goldiez, General Manager at SFEG claims that after the implementations of the cobots in their lines they have seen an increase of 20 percent in productivity. This as a result of having a pacesetter with the cobots working, hand in hand with humans. SFEG have seen the ability to get more competitive on a global scale when they go out looking for new business and they are now bringing back business from China (Modern Applications News 2016; Universal Robots 2016c).

Sambrina Thompson, Line Lead at SFEG experienced that the employees were anxious when the cobots first arrived to SFEG. But this changed after they realized that the technology just took over monotonous, dangerous and repetitive tasks. Workers could now rather concentrate on more challenging and value -added tasks. After a short period of time they were more eager with finding new areas they can use them to automate (Universal Robots 2016c; Modern Applications News 2016).

According to Jamie Cook, Lead Programmer at SFEG, the implementation time of the cobots was decreased with 30-50% based on his experience from previous implementations with traditional fixed industrial robots with more safety equipment and more effort to program. The collaborative UR robots comes with a touch screen where all programming can be performed due to arrow keys on the screen or by grab the robot arm and lead movements between waypoints. Teaching the movements to let the cobot perform certain tasks. This eliminates the time consuming structured text programming used on traditional industrial robots (Modern Applications News 2016).

By the Modbus protocol used in the specific cobots from “UR Robotics” it is possible to read the robot-status through Modbus TCP connections and by the internet socket it is possible to pass information to other software packages to collect data. This opens many new doors to do many new things that SFEG have just begun to investigate according to Jamie Cook, Lead Programmer at SFEG (Modern Applications News 2016; Universal Robots 2016c).

Figure 4-4 below shows a UR5 and a UR10 working in tandem by communicate with each other by Modbus communication. Moving field parts through a wire cutting application and on to a packing conveyor for final assembly.



**Figure 4-4. U5 and U10 working in tandem.** (Modern Applications News 2016)

SFEG have started applying new applications due to collecting life cycle data of their products. Using the cobots to collect data when live testing new designs. For example, by testing their electrical motors; Programming their mobile cobots to sequentially start and stop the electric motors with a ratio of 60 seconds running and 30 second stopped for the next 400 hours. This specific test-routine took them 5 minutes' setup time and no need for implementation of safety equipments.

The data collected must be in relevance to the product tested. An electrical motor in this case are benchmarked for specifications such as maximum amperage, minimum amperage and number of cycles performed. Received data from these testes will be stored on a database. By this, SFEG have started to apply cobots due to collecting life cycle data of their products, and engage their customers to participate in the testing as well. Showing the customers how SFEG is capable to push their design faster into production. SFEG are now after the influx of cobots starting to win more orders and taking back work that used to be outsourced to China (Modern Applications News 2016; Universal Robots 2016c).

The UR cobots at SFEG were purchased through the distributor “Cross Automation”, and according to sales Engineer Karl Bentz at Cross Automation, Cross Automation are experiencing an increased demand for their collaborative robots. “As was case at SFEG, once we sell one UR robot, the customer starts realizing what other tasks they could automate”, says Karl Bentz (Modern Applications News 2016).

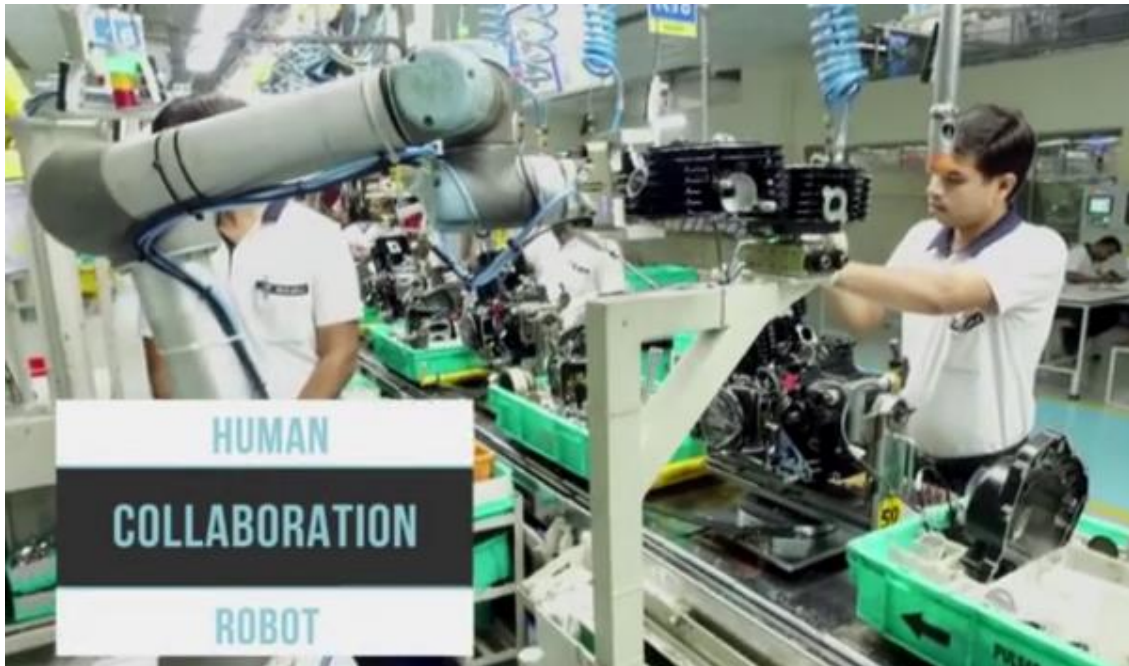
Today all future applications at SFEG are now being designed around collaborative robots. *“We’re looking at everything we’re designing now to make sure we can assemble it with a robot. If we can’t put that together with a robot, we’ve got to go back to the drawing board and try again”*, says Matt Bush, Director of Operations at SFEG (Universal Robots 2016c).

#### 4.1.2 Bajaj Auto Ltd. – The first Indian company to implement the use of collaborative robots in automotive assembly lines.

Bajaj Auto Ltd was the first Indian company to implement the use of cobots in automotive assembly lines in 2010. Five years later in 2016 they have more than 100 cobots installed in their production facilities and are the world’s 3<sup>rd</sup> largest motorcycle manufacturer with 3.3 million sold vehicles in 2015. Bajaj Auto Ltd. is an example of giving power to the workers armed with cobots as an assistant (Universal Robots 2016b).

Vikas Sawhney, General Manager at Bajaj Auto, explains that the company in 2010 was looking for solutions to automate their assembly lines. The assembly lines are highly labor intensive, have space challenges and different taxing movements that requires precisions. There was also an emerging requirement about multi modeling and adaptability, so they were looking for widespread automation with high degree of standardization.

In this development process, productivity, flexibility, reliability and the ergonomics for the workers was their main focus. They continued trying to replace repeatedly tasks from the humans to the robots, and finding the right kind of working positions for the workers (Universal Robots 2016b). Figure 4-5 below shows workers cooperating with their robot assistants, assembling motor cycle engines.



**Figure 4-5. Workers with their robot assistants assembling motor cycle engines.**  
(Panday 2016)

When Bajaj Auto was searching for suitable cobots for their assembly lines, they carried out an extensive survey of all available cobots on the market at that point of time. Specifications and features they were searching for were in relation to flexibility, affordability, compact, lightweight and safe to work with humans. A motorcycle assembly line has a typical pitch dimension of one meter and this adds the premise for the cobot to be compact and lightweight.

Their choice fell on the Danish founded company Universal Robots, and they were testing these specific robots for three months. Bajaj Auto concluded the cobots to be safe and met all their functional requirements.

*After an intensive study of the options that were available in the market, Bajaj Auto chose Universal Robots primarily due to the collaborative nature of the robots. The key benefits of Universal Robots' products such as their compactness, low pay back period, flexibility, light weight, cost-effectiveness, accuracy and their safety, is what ultimately convinced Bajaj Auto about the suitability of Universal Robots for its standardized offerings, says Vikas Sawhney, General Manager at Bajaj Auto.*



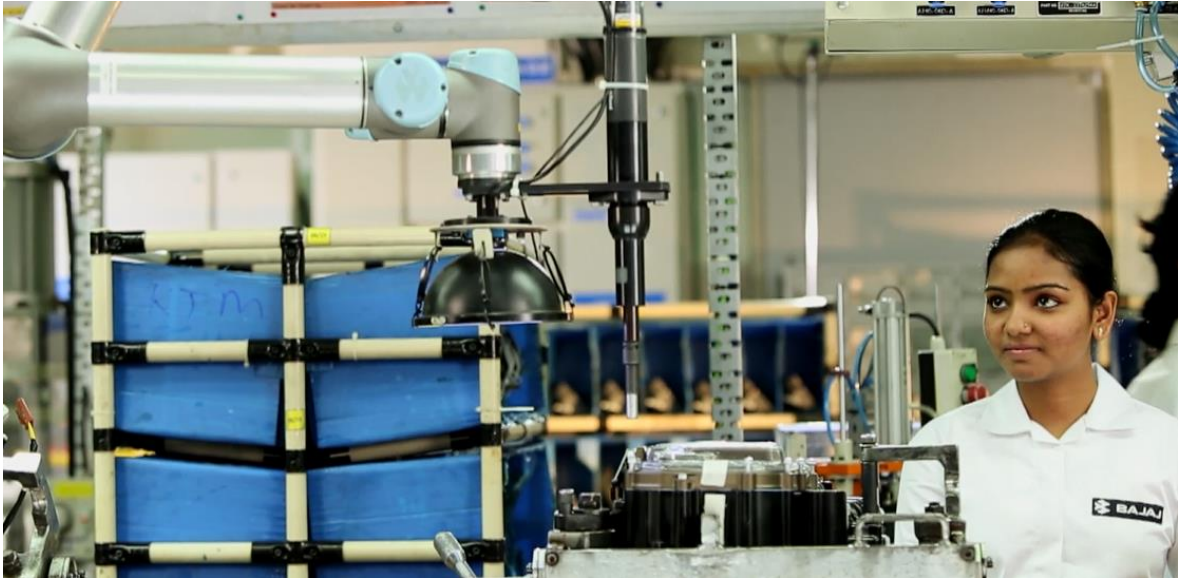
Bajaj Auto later on deployed the cobots for various applications as machine tending, material handling and also special processes as patented decal applications (Universal Robots 2016b).

According to Sawhney, the personnel productivity at Bajaj Auto (2016) have grown from 507 to 804 vehicles per person per year, which is a 58.8 percent increase of vehicles per person per year (Panday 2016).

Sawhney says that cobots is a relative new entry in the world of automation and already the cobots have found increasing acceptance in their production where precision and flexibility is a critical component in relation to the tasks they are performing. (Express News Service 2016)

Bajaj Auto's supplier, Universal Robots decided in 2015 to open an office in India because of the growing demand for cobots in the country. According to Manager in Universal Robots, Pradeep David; "*cobots increases productivity and precision of the process. It also allows workers to be better employed*". This contrasts with popular beliefs that automation leads to job losses. Davis says that this is not the case, it is rather the opposite (Express News Service 2016).

By introducing cobots in Bajaj Auto's factories the they have removed barriers for women in assembly line and by that increased the participation of woman to 50 percent of the total workforce (Express News Services 2016). Rameshwari, assembly line operator at Bajaj Auto tells in an interview about how life have changed for the workers in the factory after the arrival of the cobots in the assembly lines (Figure 4-6).



**Figure 4-6. Rameshwari, one of many women deployed in Bajaj Auto. (Panday 2016)**

Rameshwari tells that the workers get the output easily without so much strain and hard work like before. The difficult and challenging tasks are now done more easily with the cobots. She mentions particularly tightening of bolts which is hard work for humans to perform and also the accuracy of the tension which is important for the end result of the product (Universal Robots 2016b).

#### 4.1.3 Continental Automotive – Integrating of collaborative robots in automotive manufacturing.

Continental's automotive factory in Spain consists of approximately 600 employees producing four million instruments for automotive per year.

Cyril Hogard emphasizes that one of the main challenges in the automotive industry are the hard competition and it is important to continuously improve the productivity. After Continental Automotive was presented for cobots they were convinced that this technology would be a cornerstone for the growth within "industry 4.0". Integrating cobots aligns with the company's already concept of "industry 4.0", will utilize the automation and IOT in their factory. The advantage due to easy integration, zero maintenance and higher productivity was the trigger for Continental to further investigate this type of robots. Today Continental Automotive use cobots to replace operators due to simply, monotonous and repetitive tasks as gluing, dispensing and validation processes of the company's PCB boards (Universal Robots 2016a).

It is not necessary with protection around the cobots and this lead to decreased installation time and less investment in safety sensors, lightning, cages and fences. The ROI (Return of Investment) of the cobots is less than 24 months. Earlier changeover time was 40 minutes when manually handling the components. With cobots they are now able to do it in 20 minutes. This gives a 50 percent reduced changeover time (Universal Robots 2016a).

According to engineer Victor Canton it is easy for operators to perform the programming through the cobot’s touch screen. With help from the distributor and with some additional training the operators were able to understand the basic of the cobots and perform programs to the end solutions after 2-3 weeks. Before the actual production start they conduct tests due to movements and cycle time in their laboratory (Figure 4-7). By this they were able to streamline and accelerate the implementation (Universal Robots 2016a).

According to Victor they decided to change the line-follow model and made the robot to be the central part (the cobot as the pacesetter), so if they at any time needed to modify the line they were not so depended on third parties. Due to this modification, the production line can be made in-house as the cobots is the central part. This solution is based on two UR 10 from UR Robotics. One for handling the components and the other for handling the products (Universal Robots 2016a).



**Figure 4-7. Testing UR10 at laboratory in Continental Automotive.** (Universal Robots 2016a)

The main benefits Continental have gain for using cobots in this line is:

- In-house control of the cobot due to easy programming and simple installation. All programming of robots is performed in-house and all modifications to be performed in-house.
- To change the operator's role on this type of line as they do not perform tasks without added value such as moving parts from one station to another. This is done by the robots and the operators are now free to focus on skilled tasks that contribute to improve the production.
- Cost reduction by bringing down changeover time by 50%.
- Collaboration and employee safety. It is safe for humans to work with the cobots. In addition, workers can access and stop the cobot at any time due to practical reasons because of the integrated safety.

In the competitive sector of automotive industry, the main challenges are productivity and quality. Cyril Hogard claims that implementing of cobots is Continental's key solution for increased competitiveness and growth in the future (Universal Robots 2016a).

#### 4.1.4 Skoda Auto - Ending the separation of humans and robots in factories.

Skoda Auto is one of the oldest car companies in the world. As part of the Volkswagen group they have been existing since 1864 and selling their vehicles across the globe. According to Ivan Slimak, general manager at the Vrchlabi plant in Czech republic, Skoda Auto have been one of the seven plants in Europe which has won the competition "Factory of the year" (Kuka Robots 2017).

Skoda Auto has hired Matador Group to produce transmissions for the Volkswagen Group and have implemented Kuka LBR Iiwa cobots in their factories where people work directly with cobots building the transmissions. Before Skoda Auto ramped up their production line with cobots, people were doing many of the tasks manually. Today cobots from Kuka are now performing tasks in collaboration with the workers. The robots take care of tasks that include accuracy, speed and ergonomics. Many of these tasks are vulnerable to inaccuracy and a small error would lead to subsequent consequences. Because of the cobots' high precision in these assembly tasks, these production weaknesses are now eliminated. The cobots also contribute to perform tasks where space is limited and it is difficult to access for humans. Many of the tasks due to transmission assembly require little space when assembling the parts, and the small-sized/lightweight robots have a considerable advantage. The previous version of Skoda Auto's production line had conventional industry robots that had to be enclosed in areas surrounded by fences and they could not work directly with humans because of safety issues. Today all safety is integrated in the cobots (Kuka Robots 2017).

According to Ivan Slimak the challenge for Skoda Auto is how to motivate and how to train their staff in producing different products with the very high requirements for the precisions and the cleanness. Stanislav Korec, head of robotics & PLC programming in Matador group claims that programming skills was one of the most challenging parts. Specially to learn a new programming language (Java) due to new production processes and the equipment. The main differences between convention applications and collaborative applications is that the complete application must be “collaborative” (Kuka Robots 2017).

Maros Mdrak, head of development and digital factory in Matador Group claims that with Kuka Iiwa there are no needs for safety barriers, safety lightning or laser scanners. All safety is integrated in the robot (Kuka Robots 2017).

#### 4.1.5 Workplace and time sharing systems – Cooperation of human and machines in assembly lines

Smaller lot sizes of customized products give an increasing demand for achieve high flexibility and changeability in assembly processes. A closer cooperation between human and robot will improve the efficiency of individual complex assembly processes. Because of this a collaborative robot has various significant advantages compared to traditional industrial robots (Kruger et al. 2009).

According to (Kruger et al. 2009) the “hybrid automation” should make use of the strengths of both sides. The robot provides the advantage of operation without fatigue and high productivity for simple tasks. The drawback is that everything the robot shall perform must be given by “follow guiding” -instructions or programming and limited abilities due to handling complex or limp parts. Humans provide human intelligence due to handling upcoming problems and quick adapt to changes, but limited by its ability to force and precision. Using a sequential division of tasks where simple robot-tasks is found upstream in the line and more complex and varied human-tasks which provide the products individual features are found downstream in the line.

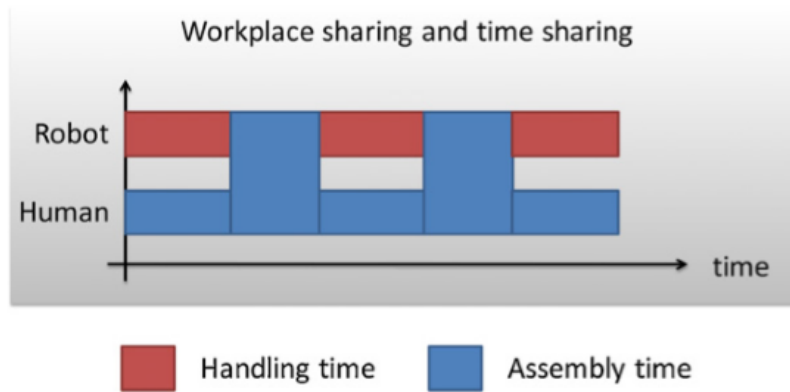
(Kruger et al. 2009) have done a research due to a hybrid “workplace and time sharing system” as follows in the below scenario. The cobot used in this explorative case study is an older type of cobot than used elsewhere in this dissertation. It is not lightweight, small-scaled or movable, but because the lack of examples of newer types of collaborative robots this example is chosen. Anyhow, the principles are the same as for today’s cobots with “following guidance” function where operator can move the end effector to desired position and also

“workplace and time sharing system”. In this case because of the size and power, the robot decrease to low speed when operator is close to the robot (inside the work space) and high speed when operator is away from the “safe zone”. Figure 4-8 below shows a workplace and time sharing hybrid system.



**Figure 4-8. Workplace and time sharing hybrid system.** (Kruger et al. 2009)

In the “workplace and time sharing hybrid system”-scenario, the tasks are to assemble heavy parts of an automobile rear drive axle. This scenario consists of two parts to be assembled. The robot first pick part A out of a box and hand it over to the worker. When the robot is entering the “shared work space” where the worker is located, the robot stops and change to cooperation mode with limited speed and all safety functions activated. In this mode the worker is able to guide the end effector on the robot by pull, push and rotate due to a very precise positioning of part A. This allows part A to be assembled with part B. When assembly task is done, the robot moves part AB to a second bin. Further the robot moves back to first bin to pick up part A’. At same time the worker will prepare part B’, which will be assembled with part A’ in the next cycle. The work load between worker and robot is shown in figure 4-9 below.



**Figure 4-9. Time distribution between worker and robot. Adopted from (Kruger et al. 2009)**

The assembly of the automotive rear axle consist of six tasks.

- Task 1: Prepare part A.
- Task 2: Grip part B out of bin.
- Task 3: Move B to A.
- Task 4: Precise positioning of part B.
- Task 5: Assembly part A and part B to part AB.
- Task 6: Move part AB to part C.

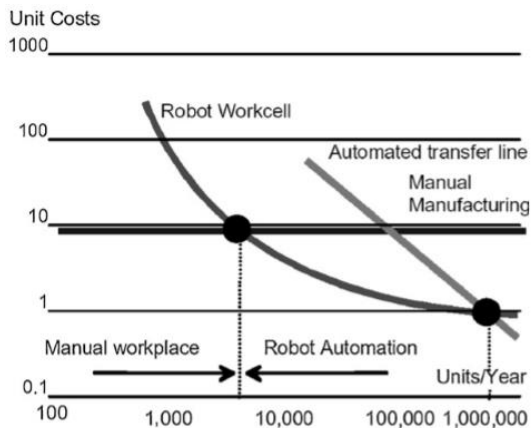
Because of the different characteristics between human and robot, the tact times will differ.

Table 4-10 below shows the different tact times.

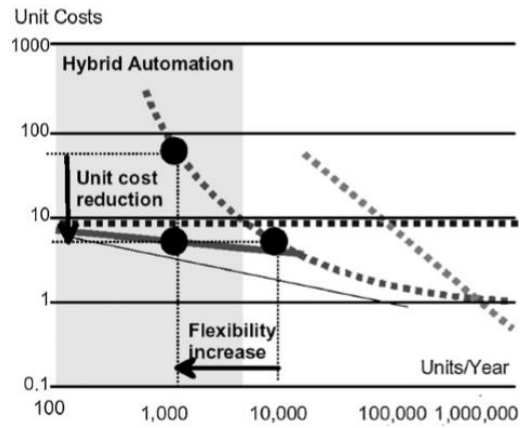
Tact times in [s]	Robot: all tasks sequentially	Human: all tasks sequentially	1 and 2,3 parallel, rest sequentially	Best of
Task 1: Prepare A	40	40	40	40
Task 2: Grip B	20	80	20	20
Task 3: Move B to A	20	120	20	20
Task 4: Precise positioning B	60	30	20	30
Task 5: Assembly	60	30	20	30
Task 6: Move AB to C	20	20	20	20
Total tact time	220	320	100	160

**Figure 4-10. Comparison of tact times between human and robot. Adopted from (Kruger et al. 2009)**

Reduction of robot system cost compared to labor cost and assumed cost potentials of future hybrid automation shows in figure 4-11 and 4-12 below.



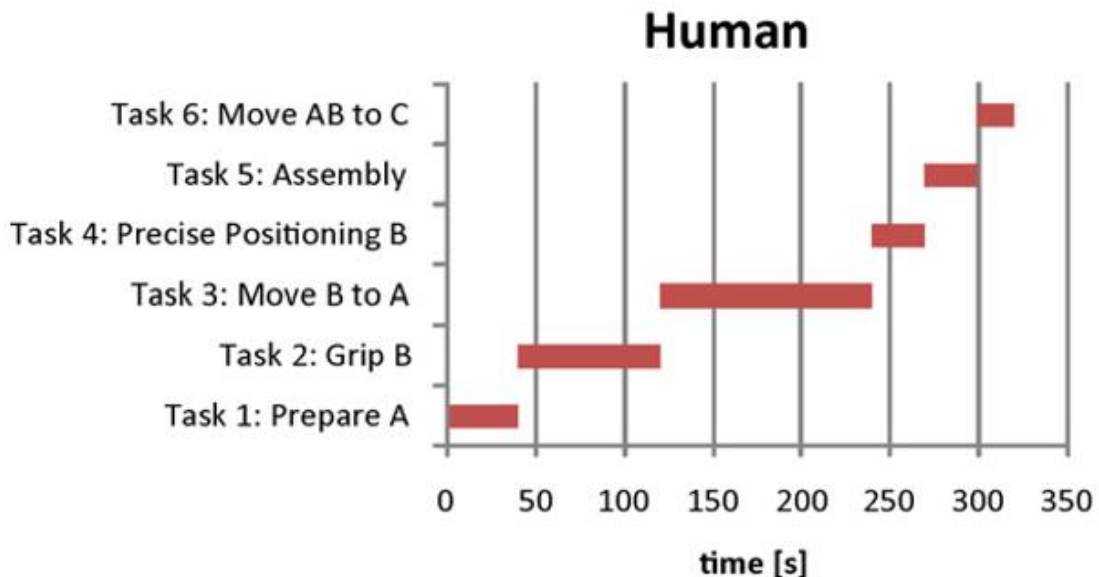
**Figure 4-11. Reduction of robot system cost compared to labor cost. Adopted from (Kruger et al. 2009)**



**Figure 4-12. Assumed cost potentials of future hybrid automation. Adopted from (Kruger et al. 2009)**

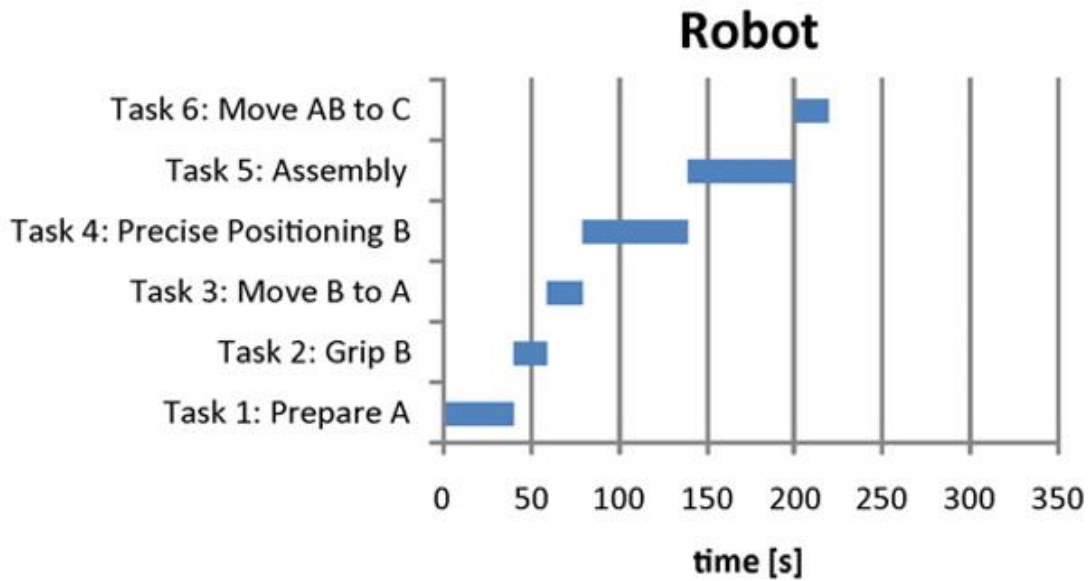
Figure 4-11 describes that producing a batch of 1-6500 units a manual production will be preferred. Production a batch of 6500-1000000 units, a hybrid solution with cobots will be preferred. If the batch size exceeds one million units a full automation with traditional industrial robots will be the best solution. The latter solution will be a mass-production.

Tact time diagrams for human, robot and hybrid shows in the figure 4-13, 4-14 and 4-15 below.

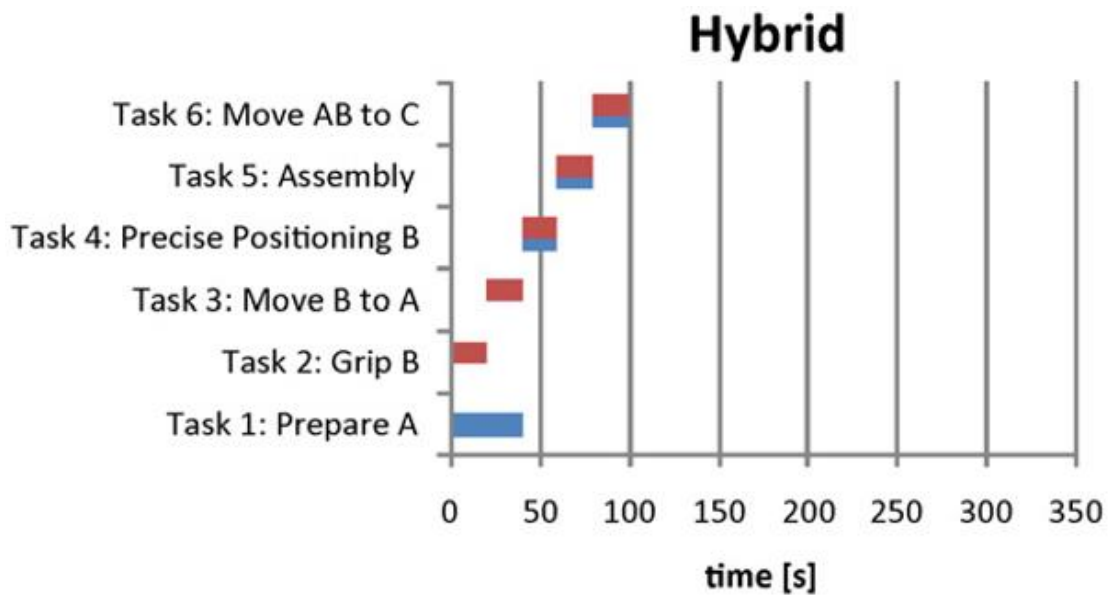


**Figure 4-13. Tact diagram, Human execution. Adopted from (Kruger et al. 2009)**





**Figure 4-14. Tact diagram, Robot execution.** Adopted from (Kruger et al. 2009)



**Figure 4-15. Tact diagram, Hybrid execution.** Adopted from (Kruger et al. 2009)

As we observe in the tact diagrams, all tasks which involves handling of heavy parts consuming more time for humans to execute. In most cases this implies unfavorable ergonomic and stressful situations for humans. It's better for the robot to handle these tasks (task 2 and 3) due to its force and endurance. Tasks 4 and 5 is better for human to handle due to human's strength of sensory skills and ability to intuitiveness by master deviations or other kind of upcoming problems. In hybrid solution task 1 is done by human and task 2 and 3 is

simultaneous done by the robot. For the Tasks 4, 5 and 6 we observe the advantage of the cooperative combination. From full human labor to a hybrid solution the time consume is reduced from 320 second down to 100 second for assembling the parts.

By compare the manual solution and the full automated solution with the hybrid solution this case unveil a high reduction of the tact time and shows that these type of solutions with cobots can have a big contribution on the economical level for manufacturing. (Kruger et al. 2009) presents several advantages of hybrid solution using collaborative robots.

- Piece-cost for assembly products to be competitive for a high variety of lot sizes compared to full automation (Traditional industrial robots).
- The integration of human gives a form of rationalization and gives positive impulses for occupation.
- Helps to avoid false investments due to cobots relatively low purchase cost.
- When relatively low lot size the assembly cost per piece are economical even.
- High reuse value of the hybrid system/cobot when change in product design.

## 5 Results / Analysis

This chapter is devoted to present the findings associated with the research question and will contain an objective description of the results. Research question is divided into three sub-questions and the findings for each of them will be presented due to the different methods of literature studies, interviews and explorative case studies applied in the thesis. This combines the results of multiple sources of evidence to ensure the measurements to become more credible by triangulation.

When applying automation, there is a risk of increasing the complexity in the manufacturing, and because of this, it is important to find the right balance of automation (Harris & Harris 2008). Collaborative robots have the advantage of reduced complexity compared to traditional industrial robots (PWC 2014). Despite the complexity of the industrial robots it has an advantage of speed (Ore 2015). It is therefore in some cases appropriate to apply this type of robot to produce the standardized parts with higher volume in a high variety environment. At the same time, it must be emphasized that collaborative robots also fit into the production of standard parts as it has shown the ability to support lean processes (ref. Table 5-2 - Table 5-5). According to the author, producing standard parts don't have the need for reconfiguration of the robot-cell so often, so both cobots and traditional industrial robots can be applied.

Further it is appropriate to apply Cobots in the production where there are need for flexibility to change between the products (Kruger et al. 2009), (PWC 2014). Collaborative robots have less structural complexity and is faster to reconfigure. These properties fit well in production of customized parts with lower volume and higher product mix (PWC 2014).

Today's global competition with everchanging market demands fits well together with the collaborative robot's quick response to changing requirements and its ability to reconfiguration of the production line with low setup cost and low time consume, proved by explorative case studies (Scott Fetzer 4.1.1), (Continental Auto 4.1.3), (Cooperation human-robot 4.1.5) and in literature (Kruger et al. 2009), (PWC 2014). Further by this underpin several of the requirements of the manufacturing system.

Below is listed some important requirements due to the environments in today's global competition that has a great impact on the performance of the manufacturing systems (Bi et al. 2008).

- **Short lead time.** (Earlier introduction of the product and an opportunity to take a bigger market share).

- **Higher product variety.** (Customizing of the product to stimulate more customers with different needs, tastes and opinions).
- **Low and fluctuating volumes.** (Shorter product life-cycle)

Table 5-1 below shows the relationship between process technologies, supply chains and the strongly connected manufacturing systems.

	Cobot	Robot	Agile	Lean	Leagile	DML	FML	RMS
High product variety (Customized parts)	X		X				X	
Low product variety (Standard parts)	X	X		X		X		
Assembled product consists of both standard- and customized parts	X	X			X			X

**Table 5-1. Relationship between process technologies, supply chains and the strongly connected manufacturing systems.**

## 5.1 RQ 1: How collaborative robots can help to create lean processes.

In the following result-tables for RQ1, the references are directly linked to “How collaborative robots can help to create lean processes” (in the second column), and to Lean in a broader perspective (in the first column). Lean manufacturing, also known as TPS (Toyota Production System) is custom oriented, have less process complexity, less scrap, less WIP (Work in Process), less inventory and less human effort (Womack et al, 1990). This is an incentive to unveil how collaborative robots can support lean processes in terms of “Doing More with Less”.

Table 5-2 below shows how collaborative robots help to create lean processes.

Lean	How collaborative robots help to create lean processes	Reference sources
Less human effort	Process optimization by the human-robot cooperation. By reallocating humans to perform more rewarding and value-added tasks and let the robots do the tasks which is not	(Kruger et al. 2009), Literature (Ore 2015), Literature (Faber et al. 2015), Literature (PWC 2014), Literature (Reuter 2016), Literature (Scholer et al. 2015), Literature (Scott Fetzer 4.1.1), Exp. case study

	suitable for humans in an ergonomically manner. Simply, monotonous, hazardous, repetitive or unergonomic tasks.	(Continental Auto 4.1.3), Exp. case study (Skoda Auto 4.1.4), Exp. case study (Cooperation human-robot 4.1.5), Exp. case study (Interview 2, 10.2.2), Interview
Less manufacturing space	Collaborative robots are in nature small scale and lightweight comparing to conventional industrial robots. They possess embedded safety and often no need for fences or cages.	(Kruger et al. 2009), Literature (Reuter 2016), Literature (Scholer et al. 2015), Literature (Scott Fetzer 4.1.1), Exp. case study (Bajaj Auto 4.1.2), Exp. case study (Continental Auto 4.1.3), Exp. case study (Skoda Auto 4.1.4), Exp. case study (Interview 1, 10.2.1), Interview
Less engineering and commission hours	Less programming hours than conventional industrial robots due to “Guide-following programming”.	(PWC 2014), Literature (Reuter 2016), Literature (Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study (Cooperation human-robot 4.1.5), Exp. case study
	Less installation hours due to no implementation of fence/cage and other safety-equipment (embedded safety in the cobot).	(PWC 2014), Literature (Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study
Less scrap	<ul style="list-style-type: none"> <li>• Appropriate division of labor between human-machine. Exploit the advantages of each of them by let the robot do the tasks the robot is good at, and let the humans do the tasks humans are good at.</li> <li>• The robot’s strength due to speed, preciseness, endurance and perform same results every time. The human’s strength due to flexibility and</li> </ul>	(Kruger et al. 2009), Literature (PWC 2014), Literature (Faber et al. 2015), Literature (Ore 2015), Literature (Scholer et al. 2015), Literature (Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study (Skoda Auto 4.1.4), Exp. case study (Cooperation human-robot 4.1.5), Exp. case study (Interview 2, 10.2.2), Interview

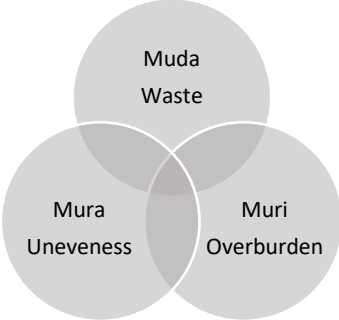
	<p>handling upcoming problems (intelligence).</p>	
	<ul style="list-style-type: none"> <li>Using both automated and manual processes, and find the right balance and the right type of automation. (Between human and robot in the same workspace)</li> </ul>	<p>(Harris &amp; Harris 2008), Literature          (Scott Fetzer 4.1.1), Exp. case study          (Scholer et al. 2015), Literature          (Bajaj Auto 4.1.2), Exp. case study          (Continental Auto 4.1.3), Exp. case study          (Skoda Auto 4.1.4), Exp. case study          (Cooperation human-robot 4.1.5), Exp. case study</p>
<p>Greater variety of products</p>	<p>Collaborative robots enable quick response to changing requirements. Time-saving reconfiguration of both HW and SW stimulates the processes for the manufacturing system to achieve rapid response to dynamical changing market demands.</p>	<p>(PWC 2014), Literature          (Kruger et al. 2009), Literature          (Faber et al. 2015), Literature          (Scott Fetzer 4.1.1), Exp. case study          (Continental Auto 4.1.3), Exp. case study          (Cooperation human-robot 4.1.5), Exp. case study          (Interview 1, 10.2.1), Interview          (Interview 2, 10.2.2), Interview</p>
<p>Decrease change-over time</p>	<p>Quick adoption to changing requirements.</p>	<p>(Kruger et al. 2009), Literature          (PWC 2014), Literature          (Scott Fetzer 4.1.1), Exp. case study          (Continental Auto 4.1.3), Exp. case study          (Cooperation human-robot 4.1.5), Exp. case study          (Interview 1, 10.2.1), Interview          (Interview 2, 10.2.2), Interview</p>
<p>Less inventory</p>	<p>By positioning the cobots where need for flexibility in the production line.</p>	<p>Referring to suggested conceptual framework (Figure 7.2 in chapter 7).          (Interview 2, 10.2.2), Interview</p>

Less WIP	Mobility. Cobot is flexible to move from current location to new location in the production line.	(Kruger et al. 2009), Literature (Scholer et al. 2015), Literature (Reuter 2016), Literature (Scott Fetzer 4.1.1), Exp. case study (Interview 1, 10.2.1), Interview (Interview 2, 10.2.2), Interview
	Connecting the cobots to a cloud-based architecture to improve the production planning. Quickly view the results for a specified machine (cobot) or the whole factory and adjust as needed.	(Waurzyniak 2015), Literature (Continental Auto 4.1.3), Exp. case study
Less process complexity	Collaborative robots give less complexity. Traditional fixed and fully automated robots require a lot of safety equipment installed around the robot-cells, this increase the complexity and make the installation expensive and time consuming.	(PWC 2014), Literature (Ore 2015), Literature (Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study (Skoda Auto 4.1.4), Exp. case study (Interview 1, 10.2.1), Interview
	Standardizing the different cobot cells and the interface between them as standard HW and SW modules. We can maintain control of complexity in the way we put together these modules when change in requirements and need for reconfiguration.	(Reuter 2016), Literature (Elmaraghy 2006), Literature (Faber et al. 2015), Literature (Scholer et al. 2015), Literature (Interview 1, 10.2.1), Interview

**Table 5-2. How collaborative robots help to create lean processes.**

Lean manufacturing is based on avoiding wastes in three ways, Muda, Mura and Muri, and refers to all kind of activities that use resources but do not create value (Liker & Meier 2006).

As above this is also an incentive to unveil how collaborative robots can support lean processes in terms of Muda, Mura and Muri:



**Figure 5-1. The three wastes in lean manufacturing.**

Table 5-3 below shows how collaborative robots help to create lean processes with respect to Muda.

Muda	How collaborative robots help to create lean processes	Reference sources
Prevent unnecessary transport, waiting and movements.	Mobility. Flexible to move from current location to new location in the production line.	(Kruger et al. 2009), Literature (Scholer et al. 2015), Literature (Reuter 2016), Literature (Scott Fetzer 4.1.1), Exp. case study (Interview 1, 10.2.1), Interview (Interview 2, 10.2.2), Interview
	Cobots to transport materials.	(Reuter 2016), Literature (PWC 2014), Literature
Prevent incorrect processing and defects.	Human handling upcoming problems due to intuitiveness, intelligence and incomparable senso-motoric abilities for complex handling tasks.	(Faber et al. 2015), Literature (Kruger et al. 2009), Literature (Ore 2015), Literature (Scholer et al. 2015), Literature (Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study (Cooperation human-robot 4.1.5), Exp. case study (Interview 2, 10.2.2), Interview
	Cobots take care of tasks due to precision and accuracy.	(Kruger et al. 2009), Literature (Faber et al. 2015), Literature (Ore 2015), Literature (Scholer et al. 2015), Literature (Scott Fetzer 4.1.1), Exp. case study (Bajaj Auto 4.1.2), Exp. case study



		(Continental Auto 4.1.3), Exp. case study (Skoda Auto 4.1.4), Exp. case study (Cooperation human-robot 4.1.5), Exp. case study (Interview 2, 10.2.2), Interview
Prevent overproducing and excess inventory	Cobots flexibility when changeover and change of market demands. Possibility for small lot size due to cobots nature of flexibility and adaptability.	(Kruger et al. 2009), Literature (PWC 2014), Literature (Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study (Cooperation human-robot 4.1.5), Exp. case study (Interview 2, 10.2.2), Interview
Prevent unused employee creativity	Cobots applied for repeatedly and monotonous tasks. Than human can do more <b>meaningful and value added tasks</b> .	(PWC 2014), Literature (Ore 2015), Literature (Scholer et al. 2015), Literature (Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study (Skoda Auto 4.1.4), Exp. case study (Cooperation human-robot 4.1.5), Exp. case study (Interview 2, 10.2.2), Interview

**Table 5-3. How collaborative robots help to create lean processes with respect to Muda.**

Table 5-4 below shows how collaborative robots help to create lean processes with respect to Mura.

Mura	How collaborative robots help to create lean processes	Reference sources
Prevent unevenness	Avoid unevenness by synchronizing both inside the cobot cell and outside the cobot cell: <ul style="list-style-type: none"> <li>• Inside cobot cell: <b>Task sharing between robot and human</b>. The robot is programmed to wait for the human to finish task before continue. Human is the pace-setter inside cell and can stop the robot at any time.</li> </ul>	(Kruger et al. 2009), Literature (Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study (Cooperation human-robot 4.1.5), Exp. case study

	<ul style="list-style-type: none"> <li>• Outside cobot cell: <b>The cobot cell can be digital connected</b> to other cobot cells and the manufacturing system.</li> </ul>	(Continental Auto 4.1.3), Exp. case study (Waurzyniak 2015), Literature (Reuter 2016), Literature
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**Table 5-4. How collaborative robots help to create lean processes with respect to Mura.**

Table 5-5 below shows how collaborative robots help to create lean processes with respect to Muri.

Muri	How collaborative robots help to create lean processes	Reference sources
Prevent overburden the equipment and people.	Put in traditional industrial robots for increased speed where bottlenecks exist and need for higher volume, and collaborative robots where flexibility is needed in the production line due to rapid changeover and reconfiguration.	Referring to suggested conceptual framework (Figure 7.2 in chapter 7).
	Inter-connecting the cobots to monitor the processes, and by this detect where deviations occur in the production.	(Waurzyniak 2015), Literature (Reuter 2016), Literature
	More intelligent production technology as cooperative robots that works closely with the workers will be able to ensure that experienced older employees can further provide an active contribution in the workplace.	(Reuter 2016), Literature (Faber et al. 2015), Literature (Interview 2, 10.2.2), Interview

**Table 5-5. How collaborative robots help to create lean processes with respect to Muri.**

## 5.2 RQ 2: How to create flexibility and reconfigurability in the production line when integrating collaborative robots.

The author will answer this question by using the Reconfigurable Manufacturing System (RMS) to support adjustable machine structure, part family focus and customized flexibility (ref. Table 5-8). Further we need to taking advantage of the inherent technical aspects which supporting both lean- and agile approach, that are naturally available in collaborative robots. And as a supplement using cyber physical solutions with a common platform to achieve the benefits of a more modular and reconfigurable digitalized production platform (ref. Table 5-9).

Today’s smaller lot size, products shorter life-cycle and greater demands for customization of products provides collaborative robots a big advantage due to flexibility and adaptability (Kruger et al. 2009), and there are several aspects to support this assertion. Due to the nature of collaborative robots, they are easy to be reconfigured and adapted into the production line where there are denuded a need for the robot cell to get fitted and set up for production. The author will answer this question by divide it into four parts:

- Manufacturing by the Reconfigurable manufacturing system.
- The technical- and process aspects of the collaborative robots which stimulate and support both agile- and lean processes.
- The process optimization aspects between human-robot collaboration.
- Cyber-physical aspects.

Table 5-6 below shows how the technical aspects associated to the collaborative robots support a more flexible and adaptable adoption to the production line.

Technical aspects of the collaborative robots.	Create flexibility and reconfigurability in the production line by collaborative robots.	Reference sources.
Small, light-weight and wheels on the cell.	Flexible and adaptable due to physical move from current location to new location in the production line.	(Kruger et al. 2009), Literature (Scholer et al. 2015), Literature (Reuter 2016), Literature (Scott Fetzer 4.1.1), Exp. case study (Interview 1, 10.2.1), Interview (Interview 2, 10.2.2), Interview
Intuitive and easy to program.	Flexible and adaptable due to reconfiguration.	(Kruger et al. 2009), Literature (PWC 2014), Literature (Reuter 2016), Literature

	<ul style="list-style-type: none"> <li>• Timesaving. Operator to “Program by guiding” of end-effector.</li> <li>• Timesaving by intuitive Graphical User Interface (GUI) by provided screen.</li> </ul>	(Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study (Cooperation human-robot 4.1.5), Exp. case study
Embedded safety.	<p>Reduce complexity of setup.</p> <ul style="list-style-type: none"> <li>• No cages/fences to consider when adapting into the line</li> <li>• Less external safety equipment’s as sensors around the cells.</li> </ul>	(PWC 2014), Literature (Faber et al. 2015), Literature (Scholer et al. 2015), Literature (Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study (Skoda Auto 4.1.4), Exp. case study
Less installation and reconfiguring time.	Less engineering hours and cost.	(PWC 2014), Literature (Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study

**Table 5-6. Create flexibility and reconfigurability in the production line by the technical aspects of the collaborative robots.**

A widespread way to share tasks between robot and human is using sequential division of labor (Kruger et al. 2009). By sharing the tasks between human and robot we can take advantage of both human and machine strengths, and by this expanding the repertoire of how and where we can use cobots in the production line. Table 5-7 below shows how the sequential division of labor stimulate to a more flexible and adaptable adoption to the production line.

Process optimization aspects of the collaborative robots.	Create flexibility and reconfigurability in the production line by collaborative robots.	Reference sources.
Sequential division of labor between human-machine based on the jobs to be performed.	With flexibility of labor-distribution, it become more applicable in relation to the work to be performed and how and where it needs to be adopted into the production line.	(Kruger et al. 2009), Literature (PWC 2014), Literature (Faber et al. 2015), Literature (Scott Fetzer 4.1.1), Exp. case study (Interview 2, 10.2.2), Interview

	<ul style="list-style-type: none"> <li>• Human: Tasks which requires flexibility and intelligence.</li> <li>• Robot: Tasks which requires precision, speed and endurance.</li> </ul>	
“Workplace sharing system” or “Workplace and time sharing system”.	When integrating into production line considerations must be given to whether it is used for: <ul style="list-style-type: none"> <li>• “Workplace sharing system” where human and robot do separate tasks in the same workspace.</li> <li><b>or</b></li> <li>• “Workplace and time sharing system” where human and robot share work on the same task in the same workspace.</li> </ul>	(Kruger et al. 2009), Literature (Bernhardt et al. 2007), Literature (Faber et al. 2015), Literature (Scholer et al. 2015), Literature (Cooperation human-robot 4.1.5), Exp. case study
	The collaboration between robot and human in the same physical workspace require a safety system. <ul style="list-style-type: none"> <li>• Light-weight with restricted action force</li> <li>• Advanced control technology for avoid collision with humans</li> <li>• Capacitive shells for the cobots</li> <li>• Cameras in certain cases</li> </ul>	(Faber et al. 2015), Literature (Ore 2015), Literature (Kruger et al. 2009), Literature (Scholer et al. 2015), Literature

**Table 5-7. Create flexibility and reconfigurability in the production line by the “process optimization” aspects of the collaborative robots.**

The author applies the Reconfigurable Manufacturing System’s focus about flexibility when adding a new cobot cell, or reconfiguration of an existing cobot cell into the production lines due to changed demands (table 5-8).

RMS are better prepared to react to disturbances occurred in the supply chains more rapidly and with higher precisions than the other manufacturing systems (Varga & Covacs 2016).

Further using the strength of RMS due to its reconfigurable skills. Unlike the other manufacturing systems, RMS have the characteristics of adjustable machine structure, part family focus and customized flexibility. RMS are using modular building blocks when designing the system for producing of a part family (Elmaraghy 2006).

Reconfigurable Manufacturing System	Create flexibility and reconfigurability in the production line.	Reference sources.
Characteristics of RMS	Integrating the collaborative robots due to RMSs following characteristics: <ul style="list-style-type: none"> <li>• Modularity</li> <li>• Convertibility</li> <li>• Customization</li> <li>• Integrability</li> <li>• Diagnosable</li> </ul>	(Elmaraghy 2006), Literature (Bi et al. 2008), Literature (Mehrabi et al. 2002), Literature (Interview 2, 10.2.2), Interview
System-level	On system level RMS consist of modular SW- and HW components: <ul style="list-style-type: none"> <li>• HW: cobots</li> <li>• SW: Control system</li> </ul> <p>The modular cobot-cells further to be arranged in serial-, parallel or hybrid configurations.</p>	(Elmaraghy 2006), Literature (Bi et al. 2008), Literature (Mehrabi et al. 2002), Literature (Interview 2, 10.2.2), Interview
Machine-level	<ul style="list-style-type: none"> <li>• Modular HW and SW components</li> <li>• Compatibility between components</li> <li>• Compatibility between components and the product-family</li> <li>• Components to be convertible due to rapid change over from one product in the family to another</li> <li>• Modules gives the system possibility to become diagnosable</li> </ul>	(Elmaraghy 2006), Literature (Bi et al. 2008), Literature

**Table 5-8. Create flexibility and reconfigurability in the production line by integrating cobots into the Reconfigurable manufacturing system.**

The advantage of the information technology and the IOT (Internet Of Things) is that everything connected to the network will integrate the existing or new resources to the manufacturing process in a new manner (Bergweiler 2016). Digitally networked processes, innovative business models, new processes and materials will make it possible to give a more flexible, resource-saving and energy-efficient manufacturing with higher degree of customization in the future (Reuter 2016). When using a Reconfigurable Manufacturing System, we also need to have rapid data sharing between machines (cobots) and manufacturing system (table 5-9). It is important to collect the information in real-time to rapid reconfiguration and by this apply information technology (Caggiano & Teti 2010), (Interview 2, 10.2.2). Interconnected automation systems are one of the important main-part of the so-called “Industry 4.0” revolution (Reuter 2016).

Cyber-physical aspects.	Create flexibility and reconfigurability in the production line.	Reference sources.
Information distribution between collaborative robot cells and the manufacturing system.	By introducing a cloud-based architecture on a common platform supporting smart devices we will achieve a <b>more modular and re-configurable production framework.</b>	(Bergweiler 2016), Literature (Waurzyniak 2015), Literature (Interview 2, 10.2.2), Interview
	Information sharing between the machines (collaborative robots) and the manufacturing system to improve efficiency, quality, reduce inventory, reduce maintenance and improve interactions with customers.	(Waurzyniak 2015), Literature (Reuter 2016), Literature
	Logging of uptime and capacity utilization allows the factory manager to quickly view the results for a specified machine or	(Waurzyniak 2015), Literature (Reuter 2016), Literature

	the whole factory and adjust as needed.	
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**Table 5-9. Create flexibility and reconfigurability in the production line by the Cyber-physical aspects.**

### 5.3 RQ 3: How to create flexibility while focusing on lean.

The author will answer this question by apply the leagile supply chain strategy and the connected Reconfigurable Manufacturing System. Below in table 5-10 is shown the different strategies used in the thesis and how they are tied up to the supply chain and manufacturing system.

	SUPPLY CHAIN			MANUFACTURING SYSTEM		
	Lean approach	Agile approach	Leagile approach	DML	FML	RMS
Supply chain strategy	Where demand is relatively stable, predictable and low variety. Forecast driven.	Where demand is volatile and high variety. Demand driven. Quick response.	Hybrid supply chain design for both lean- and agile supply chain strategies when integrating.	Lean supply chain.	Agile supply chain.	Leagile supply chain.
Variety implementation strategy	Low mix/high volume.	High mix/low volume. (Mass customization).	Custom assembled. High variety. Higher cost.	Using lean principles. (Predictable standard products).	Using agile principles. (Unpredictable customized products).	Using both lean- and agile principles for standard and customized products
Process technology strategy	Cobots/ Industrial Robots	Cobots	Cobots/ Industrial Robots	Fixed automation. More technical complex. Less complex in their operation.	More technical complexity. Variety in operations (Change over).	Reconfigurable when changed demands
Objectives	Minimum cost and high standardization	Maximum Customer service	Max. customer service while min. cost. Standardizations on predictable std. parts.	Fixed installation. Lack of flexibility.	Embedded functionality in equipment's gives more general flexibility.	Rapid reconfig. by HW/SW-modules. Flexibility due to part family.

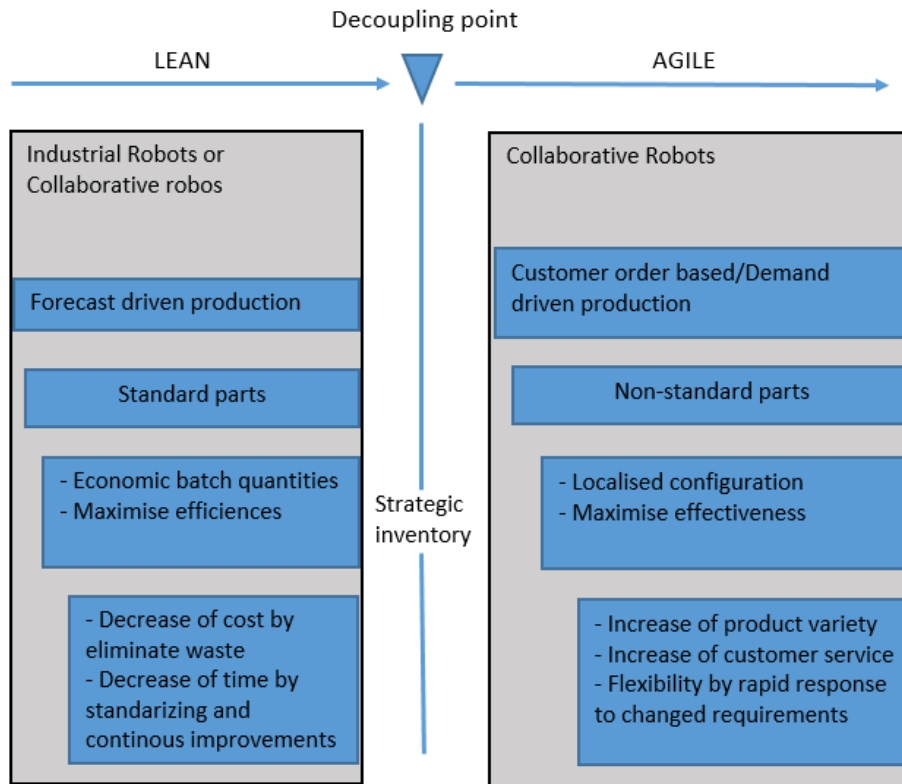
**Table 5-10. Strategies for the supply chain and the connected manufacturing system.**



Leagile is a concept usually applied when the customers have different individual needs and the products is characterized as “custom-assembled”. By combining both lean (cost and standardization) and agile (variety and flexibility) to producing higher mix of the products with often lower volumes and higher manufacturing cost. (Varga & Covacs 2016), (Naylor et al. 1999)

We first need to define the product family and by this each of the components to produce due to find the intersection between lean and agile using the decoupling point. Standard parts (lean approach) have a stable demand and is forecast driven while customized parts (agile approach) are order driven. Based on these characteristics it is possible to plan which type of process technology that is suitable for producing the products consisting of these different types of parts. A product can consist of several sub-products and these to be divided into the same principles where some of the parts are standardized and some are customized with high variety. According to the author, producing standard parts don't have the need for reconfiguration of the robot-call so often, so both traditional industrial robot and cobots can be applied. On the other hand, a collaborative robot is more appropriated for producing customized parts because of the collaborative robot's strength due to rapidly reconfiguration when change of parts in the product family (Kruger et al. 2009), (PWC 2014), (Scott Fetzer 4.1.1), (Continental Auto 4.1.3), (Cooperation human-robot 4.1.5).

Figure 5-2 below shows the process technology strategy and the product process for Leagile manufacturing using both lean- and agile manufacturing approaches to create the appropriate variety in the product line/product-family:



**Figure 5-2. Process technology strategy and the product process, Leagile Manufacturing. Adapted from Naylor’s theory on leagility.**

This supply chain strategy assesses where the structure and inventory stock holding point (DP) is located and where and when to adopt lean manufacturing for low variety demands and agile manufacturing for high variety demands. By using leagility, the supply chain goes from a pure lean supply chain to one that incorporates agility from the inventory stock holding point and downstream (Naylor et al. 1999).

Table 5-11 below shows how leagile supply chain stimulates flexibility in the manufacturing.

Multiple supply chain strategy	Create flexibility	Reference sources
Leagile approach is appropriated when increased global competition, higher variety, shorter product life-cycle	Combining multiple supply chain between agile- and lean approach to be able to focus on both cost and service level for product differentiation.	(Christopher et al. 2006), Literature (Naylor et al. 1999), Literature (Interview 2, 10.2.2), Interview

and more complex products.		
	Position of DP to meet the customer requirements.	(Naylor et al. 1999), Literature (Interview 2, 10.2.2), Interview
	Market knowledge.	(Naylor et al. 1999), Literature (Christopher et al. 2006), Literature (Interview 2, 10.2.2), Interview

**Table 5-11. How leagile supply chain create flexibility in the manufacturing.**

The above mentioned leagile supply chain is strongly connected to the Reconfigurable Manufacturing System (RMS), and combining the strengths with both the Dedicated Manufacturing System (DML) and the Flexible Manufacturing System (FMS) (Varga & Covacs 2016).

Because of the increasingly global competition, increasingly product complexity, higher variety and the decreasingly product life-cycle, the industry faces some challenges in terms of obsolescence of the manufacturing systems. By using RMS we prolong the lifetime of the system and we ensure that the system become easily upgradable and facilitating the possibility to add and remove new functionality (Elmaraghy 2006).

Table 5-12 below shows the characteristics of RMS. The focus is about flexibility and results in low stock and shorter production time.

Reconfigurable Manufacturing System	Create flexibility	Reference sources
RMS is a hybrid of DML (connected to lean supply chain) and FMS (connected to agile supply chain). Combine the advantage of both manufacturing systems to create flexibility when need for reconfiguration.	Increased flexibility in the manufacturing line due to the adjustable machine structure. <ul style="list-style-type: none"> <li>• Modularity and integrability due to HW/SW modules</li> <li>• Convertibility and customization due to Part family system</li> <li>• Diagnosable</li> </ul>	(Bi et al. 2008), Literature (Elmaraghy 2006), Literature (Mehrabani et al. 2002), Literature (Interview 2, 10.2.2), Interview

	<p>This flexibility is the foundation for being able to have short lead time, more product variants and to cope with low and fluctuating volumes.</p>	
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**Table 5-12. How the Reconfigurable Manufacturing System create flexibility.**

## 6 Discussion and conclusion

At the outset of this thesis the author was basically planning to write about lean and collaborative robots. During the work with literature review the author realized that collaborative robots have a quick response to changing requirements and an ability to reconfiguration of the production line with low set up cost and low time consumption. These characteristics of collaborative robots were further proved also in the explorative studies, and it showed that collaborative robots were implemented in industries with high variability. Parallel with this research, the author found it appropriate to investigate how collaborative robots contribute to creating lean processes. The evidences of collaborative robot's capability for quick response to changing requirements and its natural skills for also supporting lean processes became quite strong.

Because of the limited discussion on flexibility in parts of the traditional lean literature, the author started to investigate the Leagile approach (Naylor et al. 1999) where a hybrid of lean- and agile manufacturing paradigms in the total supply chain was introduced. Based on this, a concept of manufacturing products consisting of both customized and standardized parts by using leagile principles was conducted.

The author did not find any specific literature about how to apply technology such as collaborative robots in a leagile manufacturing. Therefore, it was hard to compare the results of the findings. The explorative case studies were mainly about the flexibility of collaborative robots, the human factor, safety, the work-division of the human-robot collaboration in the cell, and further how to integrate these cobots into the production lines. In the literature, these topics are mainly discussed individually, without combining them into a system. Therefore, the subchapter 2.7, which originally should be a literature review about how to integrate collaborative robots into a leagile manufacturing system, became a synthesis; i.e. the "theoretical framework for collaborative robots in leagile manufacturing".

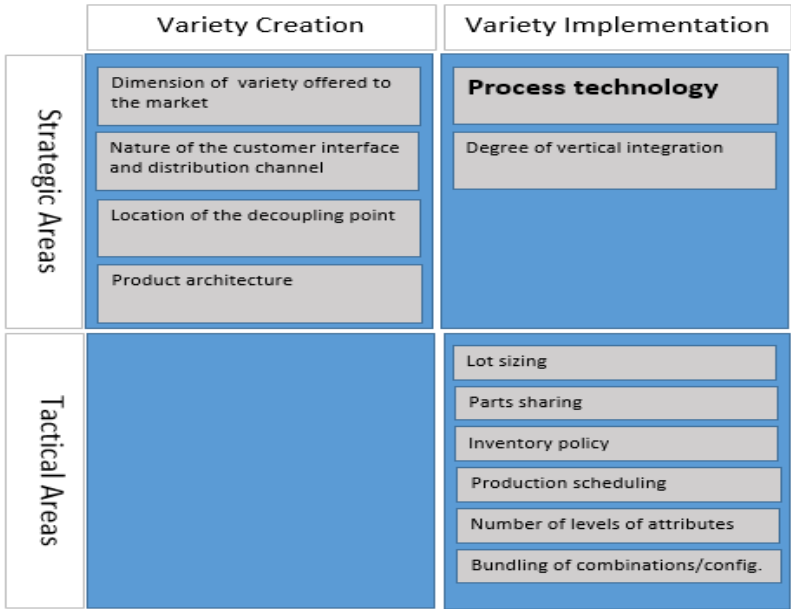
Given the gap in the existing literature on the concept of "collaborative robots in leagile manufacturing", the author is convinced that the explorative methods and experts interviews applied in the thesis are appropriate to approaching the research problem.

The author did not find any mismatch between the different sources applied in the thesis, and further, the author made a great effort to find the most relevant sources in relation to the chosen sources applied in the thesis. Most of the authors from these sources have published

several papers on the same subject over time. A triangulation between papers of same topics was also conducted to achieve good reliability.

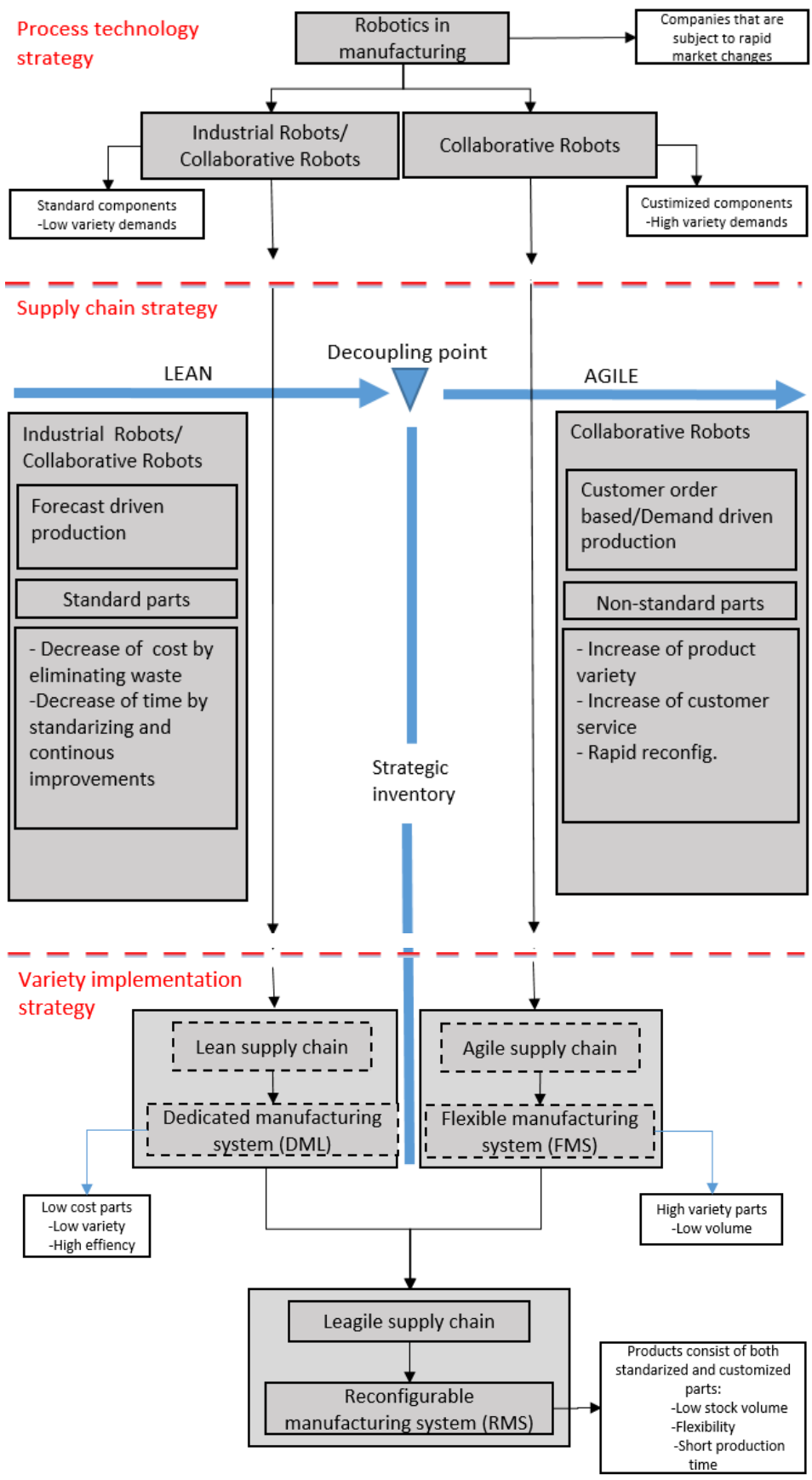
To the best of one’s knowledge, an in-depth discussion on how collaborative robots fit into established supply chain strategies (i.e. lean, agile, leagile) is lacking from the academic literature. This motivated the study at hand, and the development of the conceptual framework presented here, to show how collaborative robots contribute to leagile manufacturing. The framework describes how to enable leagile manufacturing by using cobots as a process technology strategy, and by this shows how to implement the product variety across the supply chain, including the manufacturing processes.

It is well established in the literature (Ulrich et al. 1998);(Kamalini 2001) that “variety creation” and “variety implementation” decisions, together, determine the firm’s responsiveness to demand- and process uncertainty. These variety decisions focus on HOW to create variety in the product line, and HOW to implement this across the supply chain. Variety management presents challenges at both strategic and tactical levels where the strategic decisions involve creating an effective variety delivery system. Figure 6-1 below shows the variety decisions. As it appears in the figure, it is **how to implement** the variety that is the focus of the author, and this by using the strategic area **process technology**.



**Figure 6-1. Process technology as an strategic area to decide how to implement variety as part of variety managing literature. Ref. Vaagen, teaching notes: Product Variety management. Based on (Ulrich et al. 1998).**

Figure 6-2 below describes the framework for how to enable leagile manufacturing by using collaborative robots as a process technology strategy.



**Figure 6-2. Conceptual framework for enable leagile manufacturing by using cobots as a process technology strategy.**

The implementation of high variety (high product mix) is accomplished by combining collaborative robots with leagile manufacturing principles. The framework Shows how collaborative robots, as a flexible workforce with the ability to handle dynamically changing demands by rapid reconfiguration and human-robot task-sharing, makes it possible to deliver high variety with least costs and disturbance of the manufacturing system. Moreover, the framework also shows how the decouple point (DP) concept can be used to establish a leagile strategy, and enable flexibility and quick configurability with least cost by the collaborative robots. On the agile side of the framework we apply cobots for the customized parts which are order-driven with high variety demands, and for the lean side of the framework we apply cobots or industrial robots for the standard parts which are forecast driven and have stable demand. (Traditional industrial robots may be preferred on the “most leanness” side of the framework.)

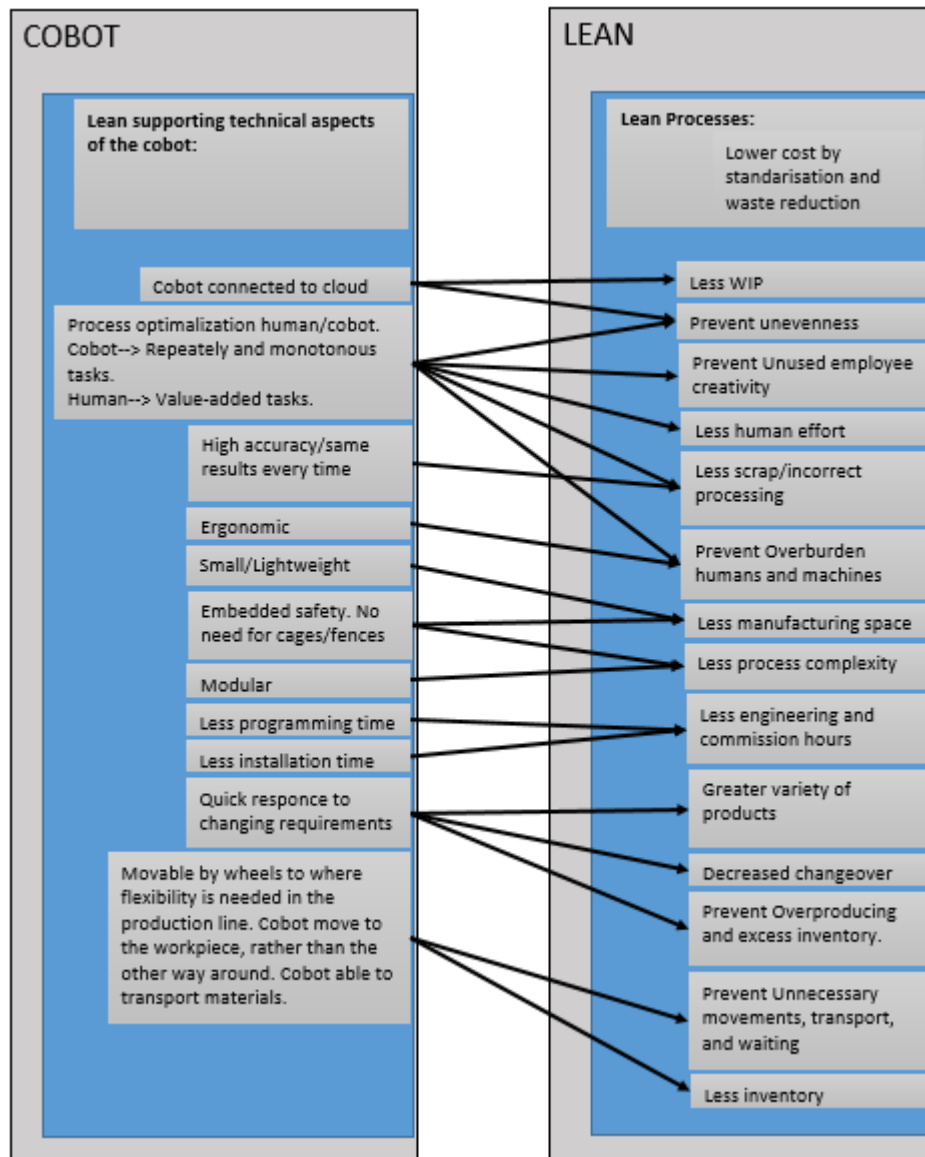
Further producing according to RMS’s part family philosophy with both standard and customized parts, with least cost and disturbance.

We needed to answer **Research Question 1**: How collaborative robots can help to create lean processes. The results we derived in the result chapter prove this capability of the COBOT systems, and are summarized below:

- Mobile
- Flexible
- Small, light-weight (less manufacturing space, easy to reallocate to new position)
- Process optimization between human-machine (Prevent unused employee creativity)
- Less engineering hour spent on programming and installation when change in demands
- Less scrap (Appropriate allocation of tasks between human-robot)
- Quick response to changed requirements, decreased change-over time and greater variety of products.
- Less complexity than fixed automation such as traditional industrial robots by the embedded safety.
- Ergonomic (Robot take care of precision, speed, repeatedly and monotonously tasks. Human take care of tasks due to sensor-motoric and intelligence)

Figure 6-3 below visualize how collaborative robots can contribute to create lean processes.





**Figure 6-3. How collaborative robots can contribute to create lean processes.**

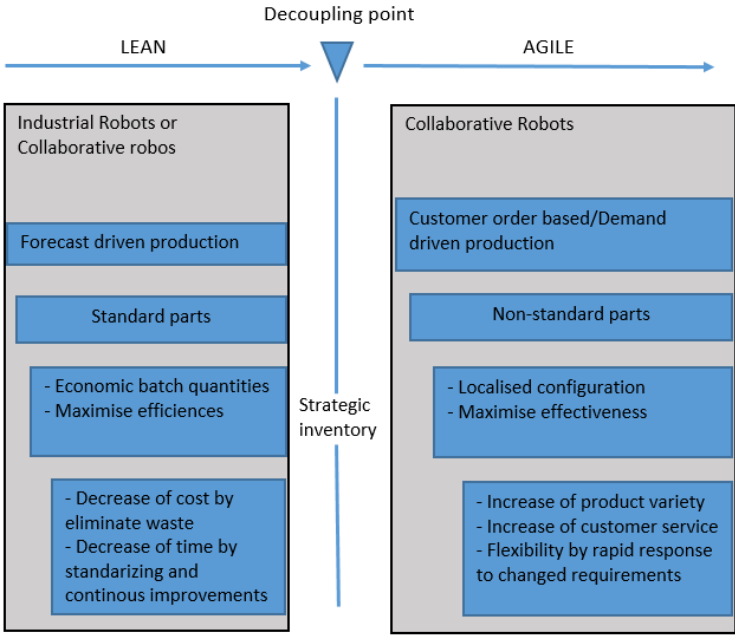
Next we answered **Research Question 3**: “How to create flexibility while focusing on lean”. The solution is to apply the multiple supply chain strategy (Leagile) and the strongly connected Reconfigurable Manufacturing System. The leagile supply chain strategy and the strongly connected Reconfigurable Manufacturing System is conducted in the conceptual framework 6.2.

To deliver high product-mix with short delivery time it is required to have a reconfigurable production line. This enables the benefits from both Dedicated Manufacturing Systems with focus on cost *and* Flexible Manufacturing Systems with focus on service level to quickly deliver a high variety. RMS quickly and precisely handles disturbances in the supply chains.

The modular building blocks and focus on part family production make RMS easily upgradable due to add/remove new cobot cells (or new functionality to existing cell). This will prevent the obsolescence of the manufacturing system and provides the desired flexibility through scalability and reconfiguration as needed to meet the market requirements.

This part family focus will help to transform the raw material into both standardized- and customized parts and will be produced in terms of the RMSs part family focus, and segmented into different groups. Further decide where to position them in the strategic stock holding inventory (DP). The standardized parts to be grouped into two types of standardizations (“ship to stock” with fixed location or “make to stock” with varied location). These two types of standardizations are forecast driven by push system and to be positioned upstream from DP in the supply chain towards lean manufacturing using Kanban to support the level production schedule for low variety demands.

Figure 6-4 below shows the process technology strategy and the product process for leagile manufacturing.



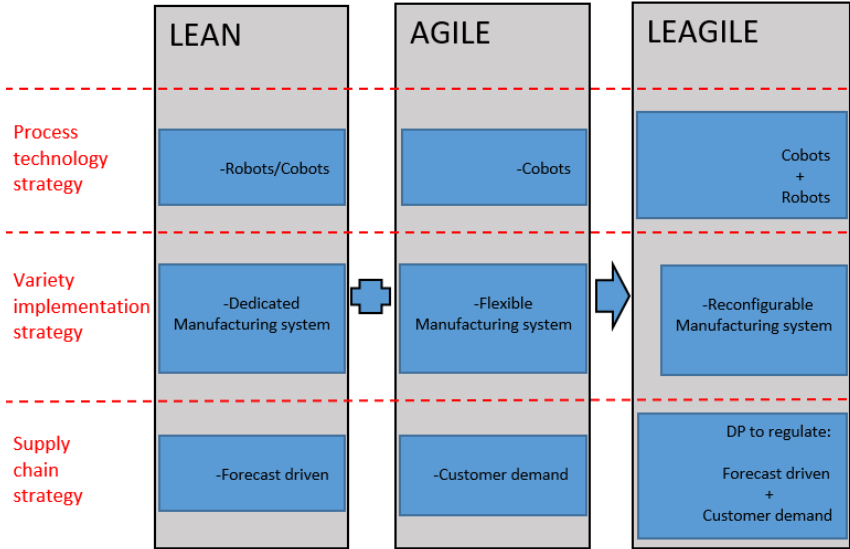
**Figure 6-4. Process technology strategy and the product process, Leagile Manufacturing. Adapted from Naylor’s theory on leagility.**

The customized parts to be grouped into three types of customizations (“buy to order” – Unique products with different raw material, “make to order” – Different products with same raw material, or “Assemble to order” – Customizing postponed to the latest stage). These

three types of customizations are customer demand driven by pull system and to be positioned downstream from DP in the supply chain towards agile manufacturing to support the flexibility for the high variety demands. As mentioned earlier, collaborative robots have a quick response to changing requirements and an ability to reconfiguration of the production line with low set up cost and low time consume. The framework is therefore developed by the following: (i) applying collaborative robots to manufacturing the customized (non-standard) high variety parts; (ii) applying agile manufacturing principles for the customized parts because agile systems support flexibility by handling rapid changes; (iii) using lean manufacturing in combination with Cobots or traditional industrial robots for the standard parts, to support standardization and low cost when higher volume.

This extrapolation of lean for the standard parts manufacturing and agile for the customized parts manufacturing into leagile manufacturing is done by applying the decoupling point concept to separate between the share of customer demand that can be predicted and the share that is prone to high variability.

As a supplement to the conceptual framework in figure 6-2, figure 6-5 below shows an overview of the process technology-, supply chain- and variety implementation strategies.

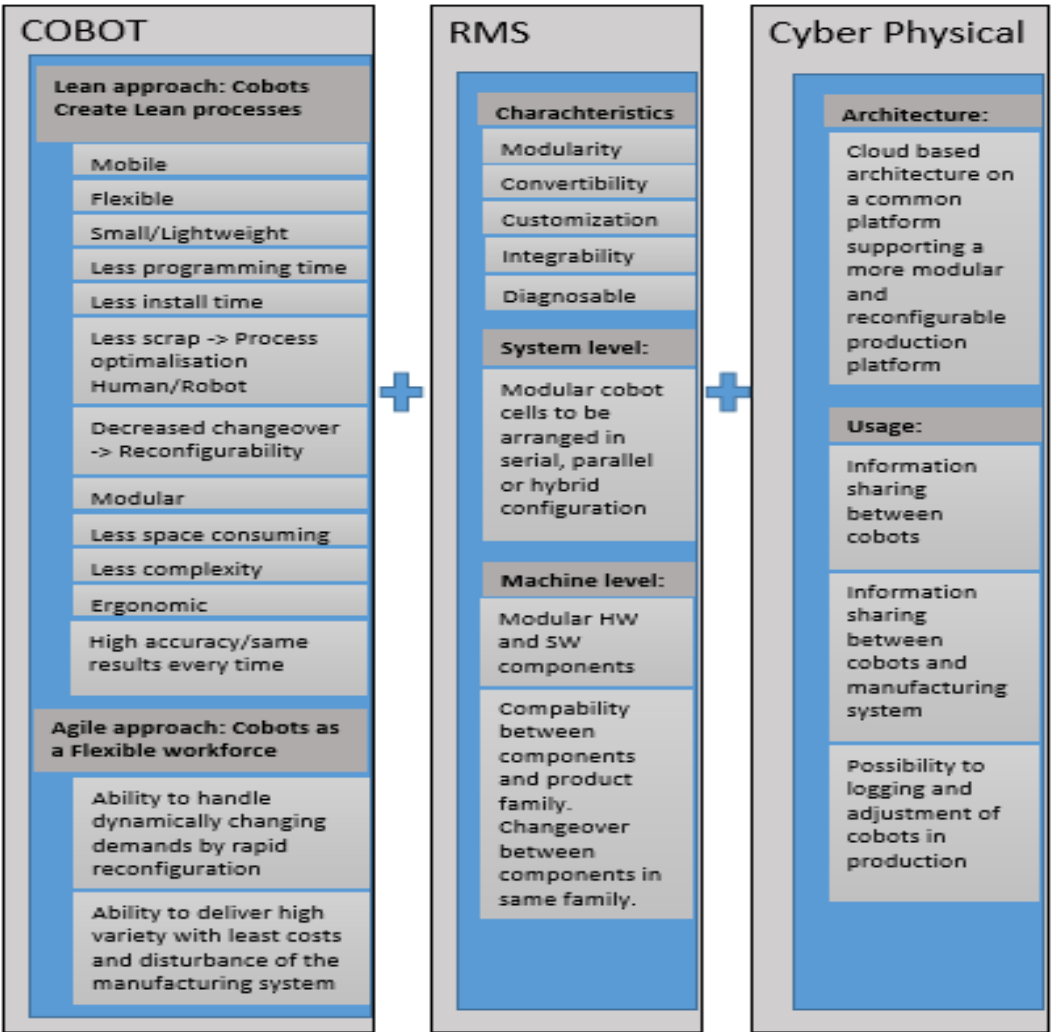


**Figure 6-5. Process technology-, supply chain- and variety implementation strategies.**

Further we answered **Research Question 2**: “How to create flexibility and reconfigurability in the production line when integrating collaborative robots”, and by this reveal the solution by using Reconfigurable Manufacturing System to support adjustable machine structure, part family focus and customized flexibility. Further we needed to apply the technical and process

optimization aspects of collaborative robots which support both rapid configuration (agile), and lean processes as described above and in the result chapter. This combination give us the advantage of flexibility and adaptability when integrating cobots into the production line. And as a supplement using cyber physical solutions with a common platform to achieve the benefits of a more modular and reconfigurable digitalized production framework. When using a Reconfigurable Manufacturing System, we also need to have rapid data sharing between machines (cobots) and manufacturing system. It is important to collect the information in real-time to rapid reconfiguration, and one of the solutions for handle this might be to use cloud systems and IOT.

Figure 6-6 below shows how collaborative robots, Reconfigurable Manufacturing Systems and cyber physical solutions together contribute to create flexibility and reconfigurability in the production line.



**Figure 6-6. Crating flexibility and reconfigurability in the production line.**

## 7 Future work

To the best of one's knowledge, an in-depth discussion on how collaborative robots fit into established supply chain strategies (i.e. lean, agile, leagile) is lacking from the scientific literature. Given the limited discussion on the topic, the conceptual framework developed in this thesis makes use of supply chain and manufacturing systems literature, as well as descriptive industrial case examples provided in the literature and media, and semi-structured expert interviews. The aim was to generate new ideas and concepts not yet fully explored by the literature. To validate, redefine (if needed) and generalize the findings and the overall framework, multiple in-depth industrial studies are suggested as future research. By applying the decouple point concept (to separate between stable manufacturing processes and those exposed to variation), the thesis emphasizes the importance of understanding uncertainty in the product line and in the supply chain. This understanding is needed in future research, to know where and how exactly to implement cobot-cells to create flexibility in the manufacturing systems, and where it is more appropriate to apply traditional robot systems, which are cost effective but less flexible.

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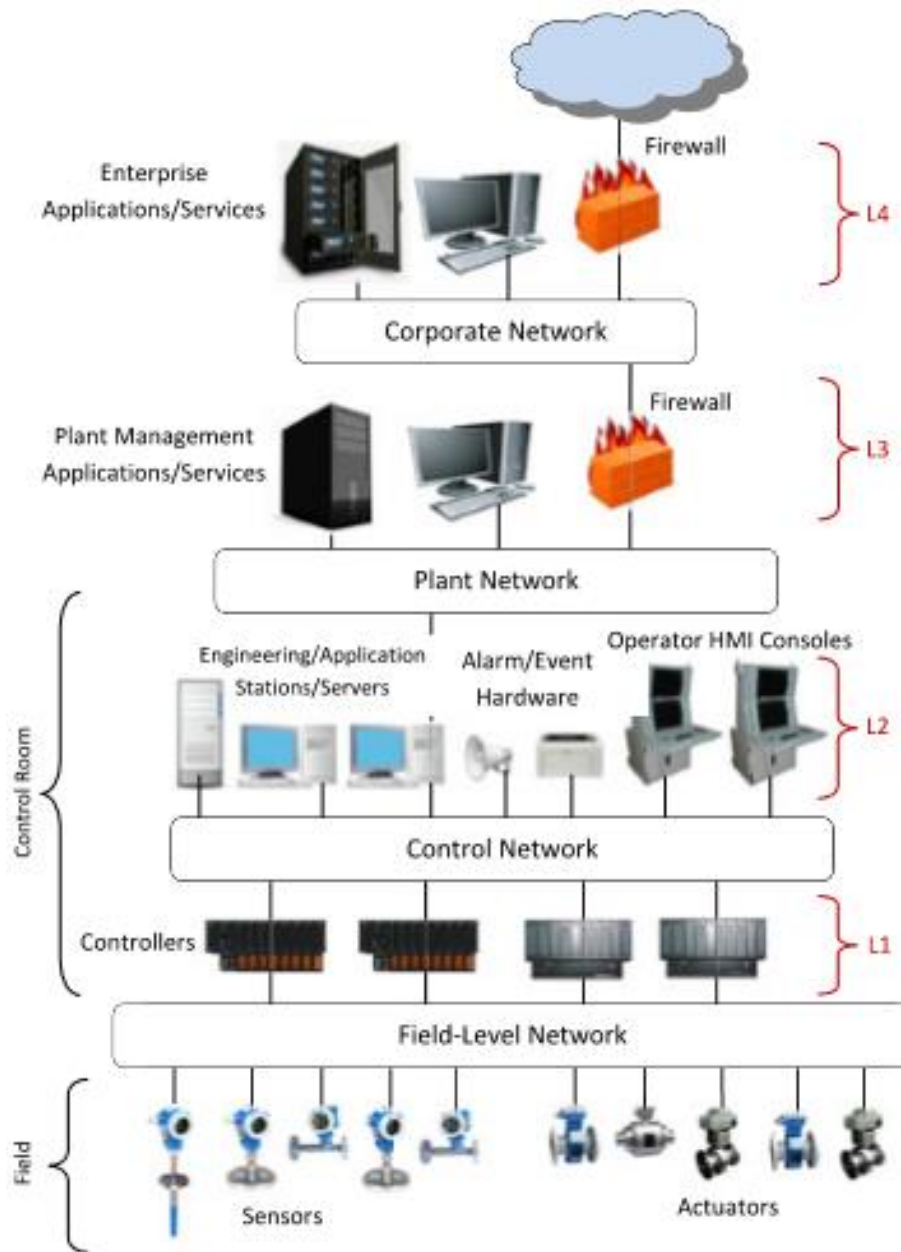
## Appendices

### Appendix A: Collaborative robots - System architecture for cloud connected robots

By using a cloud-based architecture supporting smart devices we will achieve a more modular and re-configurable production framework, and machines, sensors and other equipment are communicating with each other and exchange data (Bergweiler 2016).

Logging of uptime and capacity utilization allows the factory manager to quickly view the results for a specified machine or the whole factory and adjust as needed. The information sharing between the machines and manufacturing network to improve efficiency, quality, reduce inventory, reduce maintenance and improve interactions with customers (Waurzyniak 2015).

To be able to incorporate several devices together and develop the overall monitoring system (Didic & Nikolaidis 2015), the easiest and most cost reducing method is to tie them together in the higher architecture layer, L3 from the internal plant network. The ISA 95 standard describes automation systems as layered architecture, showed in figure 1 below:



**Appendix A figure 1.** Architecture of automation systems, adopted from (Hegazy et al. 2015)

The author wants to describe the following system architecture because the principles are the same for all types of automation systems, and this is the basic for all factory installations consists of robotic technologies in the industry. In the lowest end of the architecture we have the field-level network (L0 layer). It consists of the sensors and actuators which is monitoring and operating the physical processes in the production. The L1 layer consist of the control

part of the automation process (programmable logic controllers). These get feedback from the sensors due to the ongoing process and are controlling the actuators. L2 layer consists of the robots, operation stations and the overall control and monitoring system. This is the layer which is visible and operable for the operators. L3 is the plant management consisting of associated applications and services for the whole plant. The top level L4 is the enterprise applications and services. L4 connects the factory to the outside environment (Didic & Nikolaidis 2015).

Nowadays we see a growing interest of networked production and IOT (Internet of Things), and some industries beginning to adapt the cloud based solutions (Hegazy et al. 2015).

## Appendix B: Interviews

In this thesis, a semi-structure interview is applied. This “non-standardized” type of interview and is often referred to as “qualitative research interview”. Combining the strengths from both structured and unstructured interviews by having both flexibility and some degree of standard. (Zhang & Wildemuth 2005) The researcher of this thesis has a list of themes and questions to be covered and this will vary between the different interviews within the various subject areas.

Position	Type of interview	Interview time
Engineer, Automation	Semi-structured	4 hours
Professor, Lean/Agile manufacturing	Semi-structured	3 hours
Others	Email	-

**Appendix B table 1.** Interview portofolio. Table-structure adopted from (Zafarzadeh 2013)

### Interview topic 1: robotics in manufacturing

The first interview is due to the various aspects of robotics in manufacturing. The interviewee is an experienced automation engineer who works with a wide range of automation solutions.

The interviewee mentioned that cobots are in nature small scale and lightweight comparing to the conventional industrial robots. Most of today’s cobots have embedded safety functions and therefore do not always need fences or cages. Cobots have good flexibility and ability to quickly reconfiguration of the production line, but at the same time it has certain limitations relative to traditional fixed robots in terms of speed, accuracy and lifting power.

The interviewee quoted that when a manufacturer start using automation or expanding already existing systems, it is an advantage of using as few automation suppliers as possible. In this way, all operators can operate the robot-cells across all the stations in the factory. This due to the operator’s familiarity to both mechanical functionality and functionality of the Graphical User Interface (GUI). This homogeneity of the fleet also allows for a certain reuse of parts across the factory. He pointed out that one of the reason for the manufacturer to make use of different suppliers may often be because of price and because certain operations are only supported by one type of robot. He mentioned that one of the solutions according to multi-brands fleet of robots may be to using a multiplatform software to support all types of robots due to the same GUI design.

The interviewee told about the importance of reduced complexity, proper automation-degree and appropriate solutions will ensure more robust systems and less interference in the line. A way to make the robot cells more easy to operate is to let the robot cell become more transparent and intuitive instead of a “black-box”. By visualize the flow in the cell, and additionally use of intuitive and “easy to learn” GUI it is easier to guide the operator through complex tasks such as performing changeovers or failure-recover. The interviewee further pointed out the importance of already having established “lean mindset” in both the processes and the employees before implementing the technology.

The interviewee also confirmed his agreement to the full automation not seem to be the future and there are several advantages of using cobots in industries with increasingly higher demands to produce customized products. The interviewee also mentioned that traditional robots have the advantage of high speed and the cobots have the advantage due to be easily movable.

Regarding benefits of cyber physical systems (cloud) where both cobots and traditional fixed industrial robots are linked together to the overall production system the interviewee was in the opinion that this may generate several advantages. First in terms of it saves a lot of hardwired cabling. All information then goes through single network cables instead of several hardwired cables, and it also allows for wireless connection if low noise and interference by the production environment. Further he mentioned the possibility for having a maintenance system for the whole robot-fleet in the factory on basis on this interconnectivity. This gives the possibility to send real time production-data to the supplier’s engineers so they can work together to optimize the equipment or production processes when installation/commissioning or on a later stadium when change in the production demand.

## Interview topic 2: lean- and agile manufacturing

The second interview is due to Agile and Lean manufacturing. The interviewee is a professor at NTNU. The questions asked was both due to the leagile approach and the connected RMS, but also how collaborative robots may fit into the established supply chain strategies.

The interviewee quoted that the leagile approach is appropriated when increased global competition, higher variety, shorter product life-cycle and more complex products. By combining multiple supply chain between agile- and lean approach to be able to focus on both cost and service level for product differentiation. Furthermore, to consider the market knowledge and the position of the decoupling point.

The interviewee told that when applying Leagile approach, the connected manufacturing system are the RMS. It consists of a modular product portfolio strategy for rapid configuration. RMS is a hybrid of both the DML and FMS. By this it combines the advantage of both manufacturing systems to create flexibility when reconfiguration is needed. This flexibility is the foundation for being able to have short lead time, more product variants and to cope with low and fluctuating volumes. The interviewee further pointed out that RMS have the characteristics of modularity, convertibility, customization, diagnosable and integrability, and consist of modular SW- and HW components. It is important to collect the information in real-time to rapid reconfiguration, and one of the solutions for handle this might be to use cloud systems and IOT.

Further in the interview, the collaborative robot's ability to promote increased performance for both flexibility and lean processes is discussed. Regarding how cobots may enable quick response to changing requirements and ensure a greater variety of products, the interviewee was in the opinion that it should be established a meaningful distribution between the human-robot work tasks. Sequential division of labor between human-robot based on the job to be performed. Human contribute to tasks which requires flexibility and intelligence, and the robot contribute to tasks which requires precision, endurance and speed. By reallocate humans to perform more rewarding and value-added tasks, and let the robots perform the repetitive tasks which is not suitable for humans in an ergonomically manner. This process optimization by the human-robot cooperation will prevent unused employee creativity and further it will decrease the human effort, and by this extend the senior workers contribution in the workplace. It may also prevent incorrect processing and less scrap. Furthermore, the cobots time-saving reconfiguration of both HW and SW will stimulate to achieve the rapid response to the dynamical changing market demands.

When it comes to how cobots may prevent unnecessary transport, waiting and movements the interviewee was in the opinion that there is a distinct advantage that the cobot is easily movable and by this it is possible to position it where there is a need for flexibility. This mobility of cobots may also help to reduce the WIP and inventory in the production

## Appendix C: Research report

The paper “Collaborative robots – a process technology strategy to enable Leagile Manufacturing” is presented here.

# Collaborative robots – a process technology strategy to enable Leagile Manufacturing.

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The collaborative approach where humans use robots as an intelligent assistant in the same workspace to achieve a common goal have become a powerful tool. Collaborative robots support quick adaptation to changing requirements, that is, they enable flexibility in the production processes, known as 'agility' in the supply chain literature. At the same time, cobots have shown capability to creating lean processes in the production line. By combining the lean and agile manufacturing paradigms in the total supply chain, a complementary positive effect with benefits from both worlds can be achieved. This paper explores the collaborative robot's ability, as a *process technology strategy*, to enable leagile manufacturing with improved performance from flexibility and lean processes, in industrial environments with high product- and process variety. The findings are summarized by a conceptual framework for leagile manufacturing through collaborative robots.

Keywords: Collaborative Robots, Leagile Manufacturing, Lean Manufacturing, Flexibility, Reconfigurability.

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## 1. Introduction

Today's society in the industrial nations is facing falling birth-rates and increasing life expectancy. It is hard to predict the productivity in the future, but digitalization of manufacturing processes and smarter machines will largely be able to make people much more effective than all generations before them. More intelligent production technology as cooperative robots that works closely with the workers will be able to ensure that experienced older employees can further provide an active contribution in the workplace (Reuter 2016).

The increasing global competition requires smaller lot sizes, products with shorter life cycles and increased demand for customization (Christopher et al. 2006). This makes it important to reveal how to increase the industrial performance for companies producing high variety products.

A collaborative approach where humans use robots as an intelligent assistant in the same workspace to achieve a common goal have become a powerful tool (Kruger et al. 2009). By combining the flexibility of human interaction and intuitiveness with the handling capacity and precision of robots will make applications lean and enhance a lean manufacturing environment (ProcessOnline 2014). This enables to find the 'right' balance and degree of automation between automated and manual processes (Harris & Harris 2008).

Traditional fixed and fully automated production cells are cost- and time consuming to reconfigure to changing market needs (Kruger et al. 2009).

Collaborative robots have shown a quick response to changing requirements and an ability to reconfiguration of the production line with low set up cost and low time consumption, proved by the explorative case studies (Scott Fetzer 4.1.1), (Continental Auto 4.1.3), (Cooperation human-robot 4.1.5) and in literature (Kruger et al. 2009), (PWC 2014).

Using agile manufacturing where we need flexibility and lean manufacturing where we need standardization and leveling scheduling. This is in manufacturing theory often referred to as Leagile manufacturing. Both paradigms have their strengths and limitations, and by carefully combine them in relation to the correct supply chain strategy will provide a complementary positive effect (Naylor et al. 1999).

The different supply chains are strongly related to associated manufacturing systems which transforms raw material into products (Bi et al. 2008). By combining both lean and agile approach, the Reconfigurable Manufacturing System (RMS) is applied (Varga & Covacs 2016). The modular building blocks and focus on part family production make RMS easily upgradable due to add/remove new cobot cells or supply with new functionalities to existing cell. This will prevent the obsolescence of the manufacturing system and provide the desired flexibility through scalability and reconfiguration as needed to meet the market requirements (Elmaraghy 2006), (Mehrabi et al. 2000). Explorative case studies have been used to provide new understanding on a new problem with limited research to generate new principles and ideas that need further research. Further it is developed a conceptual framework for showing how to enable leagile manufacturing by using collaborative robots as a process technology strategy, and by this shows how to implement the product variety across the supply chain, including the manufacturing processes.

Figure 1-1 below shows the main topics of the research.



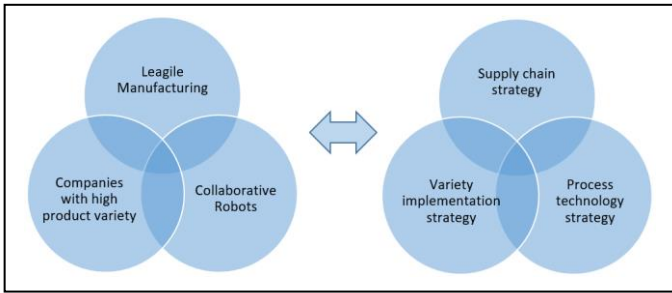


Figure 1-1. Main topics for the research.

## 2. Collaborative robots in manufacturing – industrial practice and state of the art literature

Increased global competition causes rapid changes in the market demands. This requires more effective business strategies and production systems, and these improvements must be made at all levels in the companies. (Ore 2015). This is a driver to take advantage of collaborative robots and simultaneously introducing productivity improvements at all levels in the supply chain.

### 2.1. Human-Robot cooperation – state of the art

Collaborative robots support the humans using their skills to perform value-added tasks more efficiently when robots perform repetitively and monotonous tasks with high precision, speed and endurance (Ore 2015), (Kruger et al. 2009). The simple tasks suited for robots to be found upstream in the line, and the varied complex tasks belonging to the customization is found downstream performed by the human operators (Kruger et al. 2009). A widespread way to share tasks between robot and human is using sequential division of labour. By sharing the tasks between human and robot we can increase the efficiency, capacity, quality and product variation and at the same time reduce the production cost (Kruger et al. 2009), and it is important to find the right balance and the right type of automation (Harris & Harris 2008).

Collaborating robot systems can be divided into two groups where both robot and human are working in the same workspace (Kruger et al. 2009), (Bernhardt et al. 2007):

- Workplace sharing systems
- Workplace and time sharing systems

In workplace sharing systems human and robot do separate tasks in the same workspace. This to be in accordance to the workload levelling.

In workplace and time sharing systems human and robot share work on the same tasks in the same workspace. In addition to avoiding collision with the human, the robot also has to interact with the human to perform the shared tasks (Schraft et al. 2005).

Today's light weight collaborative robots are easy to move between different locations in the plant, and easy to reconfigure when change of customer demand, and are an excellent example of how we can use collaborative robots in much larger scale with several advantages (Kruger et al. 2009):

- Cost reduction due to the combined strengths of human and robot.
- Improvements of the ergonomics situation for humans.
- Availability and flexibility due to where to install.
- Parallel task operation between human robot to increase efficiency.

### 2.2. Leagility – Combining lean and agile manufacturing in the total supply chain - state of the art

The choice of a supply chain strategy has become more and more important because of the global competition, the complexity of the products and the short lifecycle of the products.

It is not about Lean vs Agile, but to combine these different concepts into a hybrid system with benefits from both worlds (Naylor et al. 1999).

Agile manufacturing is best suited to satisfying a changing production demand in terms of variety and volume (Naylor et al. 1999). According to (Christopher et al. 2006), lean concepts is suitable for relatively stable customer demands and when variety is low.

The supply chains consist of a network of different elements as resources, activities and organizations connected to stimulate the market demands (Varga & Covacs 2016). These different supply chain members contains the material suppliers, distribution services, production facilities and all customers tied together via material feed-forward and information feed-back system. (Naylor et al. 1999).

The total supply chain strategy when combining Lean and Agile must consider the market knowledge and the position of the decoupling point (DP). The key difference between Lean and Agile manufacturing paradigm will determine the location of the decoupling point due to meet the customer requirements. This location of the decoupled point is where to place the strategic buffer between dynamically changing customer demands and smooth production. The DP is crucial when considering when to use Lean or Agile manufacturing techniques.

Downstream from the DP consist of high product variety with high variable demand. Upstream from the DP the demand is decreased with less product variety. Because of this we know that the point of product differentiation is at the DP or downstream from the DP (Naylor et al. 1999).

Agile manufacturing will ensure the production processes to have a quick response due to changing requirements from the market, rapid reconfiguration of the production processes and therefore the possibility to change to a wide range of products within the product family. This increases flexibility and further shows that "Agility focuses on service levels for product differentiation".

Agile manufacturing will eliminate as much waste as possible but it is not prerequisite. Lean manufacturing will ensure to eliminate all non-value waste in the production process. Lean manufacturing also will be as flexible as possible but it is not prerequisite (Naylor et al. 1999).

## 3. Conceptual framework development

The explorative cases and literature study led to the development of a conceptual framework, summarizing the main ideas and concepts on how, exactly, collaborative robots enable to create leagility, through flexible (agile) processes, while still cost-effective and efficient (lean) processes.

This exploratory type of research does not usually provide conclusive evidence, but intends to explore the research question by outline the problem better. Unlike a conclusive research which output is a concluding answer of the research question, the exploratory research contributes to a better understanding of the problem with varying levels of depth without necessarily providing the final answers (research-methodology.net 2017). A triangulation between the different methods applied such as literature study, interviews and explorative case studies has been performed.

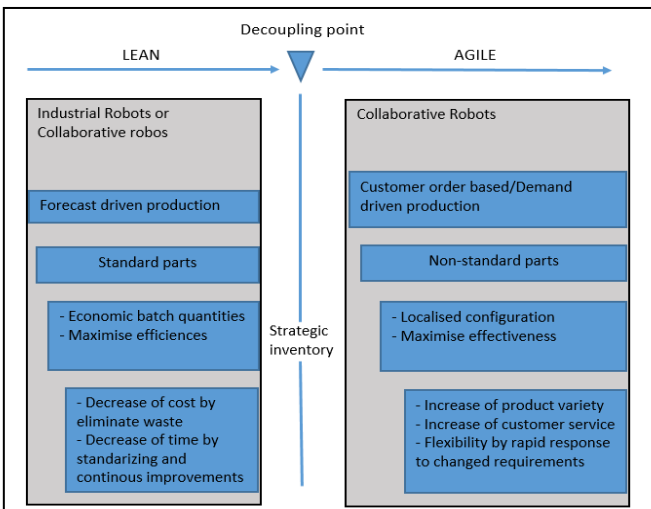
It is well established in the literature (Ulrich et al. 1998) and (Kamalini 2001) that "variety creation" and "variety

implementation” decisions, together, determine the firm’s responsiveness to demand- and process uncertainty. These variety decisions focus on HOW to create variety in the product line, and HOW to implement this across the supply chain. Variety management presents challenges at both strategic and tactical levels where the strategic decisions involve creating an effective variety delivery system. It is how to implement the variety that is the focus of the author, and this by using the strategic area process technology.

The conceptual framework will contribute to create flexibility while focusing on lean by using Leagile as the multiple supply chain strategy combined with using cobots as a process technology. By this, incorporate agility from the strategic inventory stock holding point (DP) and downstream. Leagile supply chain strategy and the strongly connected Reconfigurable Manufacturing System is conducted in the conceptual framework.

To deliver high product-mix with short delivery time it is required to have a reconfigurable production line. This enables the benefits from both the Dedicated Manufacturing System with focus on cost and the Flexible Manufacturing System with focus on service level to quickly deliver a high variety (Elmaraghy 2006)(Mehrabi et al. 2000). The RMS quickly and precisely handles disturbances in the supply chains (Varga & Covacs 2016). The modular building blocks and focus on part family production make RMS easily upgradable due to add/remove new cobot cells or new functionalities to existing cell. This will prevent the obsolescence of the manufacturing system and provide the desired flexibility through scalability and reconfiguration as needed to meet the market requirements (Elmaraghy 2006), (Mehrabi et al. 2000).

This part family focus of the RMS (Elmaraghy 2006) will help to transform the raw material into both standardized- and customized parts (non-standard parts) and will be produced in terms of the RMSs part family focus, and segmented into different groups. Further decide where to position them in the strategic stock holding inventory. The standardized parts to be grouped into two types of standardizations (“ship to stock” with fixed location or “make to stock” with varied location). These two types of standardizations are forecast driven by push system and to be positioned upstream from DP in the supply chain towards lean manufacturing using Kanban to support the level production schedule for low variety demands (Naylor et al. 1999). Figure 3-1 below is visualizing the process technology strategy and the product process for the leagile manufacturing.

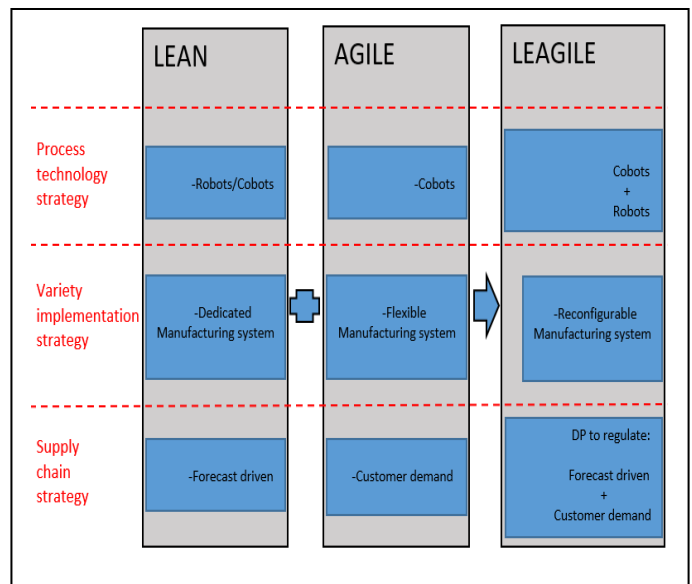


**Figure 3-1.** Process technology strategy and product process, leagile manufacturing. Adapted from Naylor’s theory on Leagility.

The customized parts to be grouped into three types of customizations (“buy to order” – Unique products with different raw material, “make to order” – Different products with same raw material, or “Assemble to order” – Customizing postponed to the latest stage). These three types of customizations are customer demand driven by pull system and to be positioned downstream from DP in the supply chain towards agile manufacturing to support the flexibility for the high variety demands (Naylor et al. 1999).

As mentioned earlier, collaborative robots enable quick response to changing requirements and reconfigurability of the production line with low set up cost and low time consume, proved by the explorative case studies (Scott Fetzer 4.1.1), (Continental Auto 4.1.3), (Cooperation human-robot 4.1.5) and in literature (Kruger et al. 2009), (PWC 2014). This is achieved by the following: (i) applying collaborative robots to manufacturing the customized (non-standard) high variety parts; (ii) applying agile manufacturing principles for the customized parts because both collaborative robots and agile systems support flexibility by handling rapid changes; (iii) applying lean manufacturing principles in combination with cobots or industrial robots to support standardization and cost-advantage for high volume production. Traditionally, fixed automation (industrial robots) are today the most widespread choice because of the cost efficiency (high speed in production), but despite this, cobots are well suited for use in lean environments because of their proven ability to make both agile and lean processes (ref. Table 3-1).

This extrapolation of lean for the standard parts manufacturing and agile for the customized parts manufacturing into leagile manufacturing is done by applying the decoupling point concept to separate between the share of customer demand that can be predicted and the share that is prone to high variability. Figure 3-2 below shows an overview of the process technology-, supply chain- and variety implementation strategies.



**Figure 3-2.** Process technology-, supply chain- and variety implementation strategies.

Furthermore, we need to integrate collaborative robots into the production line by using Reconfigurable Manufacturing System to support adjustable machine structure, part family system focus and customized flexibility (Figure 3-3).

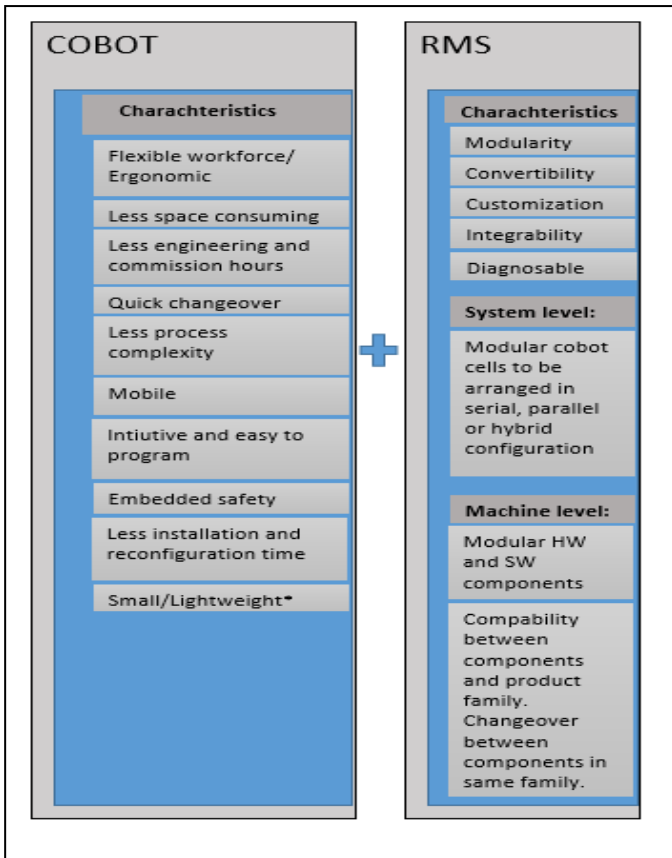


Figure 3-3. Integrating collaborative robots into the production line

Table 3-1 summarizes the characteristics of collaborative robots supporting leagile production lines (ref. figure 3-3), along with reference to the relevant literature.

Characteristics of cobots	Supporting leagile processes	Reference sources
Flexible workforce. Process optimization (Less human effort)	Process optimization by the human-robot cooperation. By reallocating humans to perform more rewarding and value-added tasks and let the robots do the tasks which is not suitable for humans in an ergonomically manner. Simply, monotonous, hazardous, repetitive or unergonomic tasks.	(Kruger et al. 2009), Literature (Ore 2015), Literature (Faber et al. 2015), Literature (PWC 2014), Literature (Reuter 2016), Literature (Scholer et al. 2015), Literature (Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study (Skoda Auto 4.1.4), Exp. case study (Cooperation human-robot 4.1.5), Exp. case study (Interview 2, 10.2.2), Interview

Less manufacturing space	Collaborative robots are in nature small scale and lightweight comparing to conventional industrial robots. They possess embedded safety and often no need for fences or cages.	(Kruger et al. 2009), Literature (Reuter 2016), Literature (Scholer et al. 2015), Literature (Scott Fetzer 4.1.1), Exp. case study (Bajaj Auto 4.1.2), Exp. case study (Continental Auto 4.1.3), Exp. case study (Skoda Auto 4.1.4), Exp. case study (Interview 1, 10.2.1), Interview
Less engineering and commission hours	Less programming hours than conventional industrial robots due to "Guide-following programming".	(PWC 2014), Literature (Reuter 2016), Literature (Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study (Cooperation human-robot 4.1.5), Exp. case study
	Less installation hours due to no fence/cage and implementation of other safety-equipment (embedded safety in the cobot).	(PWC 2014), Literature (Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study
Quick changeover/ Generate greater variety of products	Collaborative robots enable quick response to changing requirements. Time-saving reconfiguration of both HW and SW stimulates the processes for the manufacturing system to achieve rapid response to dynamical changing market demands.	(PWC 2014), Literature (Kruger et al. 2009), Literature (Faber et al. 2015), Literature (Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study (Cooperation human-robot 4.1.5), Exp. case study (Interview 1, 10.2.1), Interview (Interview 2, 10.2.2), Interview
Less process complexity	Collaborative robots give less complexity. Traditional fixed and fully automated robots require a lot of safety equipment installed around the robot-cells, this increase the complexity and make the installation expensive and time consuming.	(PWC 2014), Literature (Ore 2015), Literature (Scott Fetzer 4.1.1), Exp. case study (Continental Auto 4.1.3), Exp. case study (Skoda Auto 4.1.4), Exp. case study (Interview 1,

		10.2.1), Interview
Flexible/mobile	Flexible and adaptable due to physical move from current location to new location in the production line.	(Kruger et al. 2009), Literature (Scholer et al. 2015), Literature (Reuter 2016), Literature (Scott Fetzer 4.1.1), Exp. case study (Interview 1, 10.2.1), Interview (Interview 2, 10.2.2), Interview
Intuitive and easy to program.	Flexible and adaptable due to reconfiguration. <ul style="list-style-type: none"> <li>• Timesaving. Operator to “Program by guiding” of end-effector.</li> <li>• Timesaving by intuitive Graphical User Interface (GUI) by provided screen.</li> </ul>	(Kruger et al. 2009), Literature (PWC 2014), Literature (Reuter 2016), Literature (Scott Fetzer 4.1.1), Exp. Case study (Continental Auto 4.1.3), Exp. case study (Cooperation human-robot 4.1.5), Exp. case study
Embedded safety.	Reduce complexity of setup. <ul style="list-style-type: none"> <li>• No cage/fences to consider when adapting into the line</li> <li>• Less external safety equipment’s as sensors around the cells.</li> </ul>	(PWC 2014), Literature (Faber et al. 2015), Literature (Scholer et al. 2015), Literature (Scott Fetzer 4.1.1), Exp. Case study (Continental Auto 4.1.3), Exp. case study (Skoda Auto 4.1.4), Exp. case study

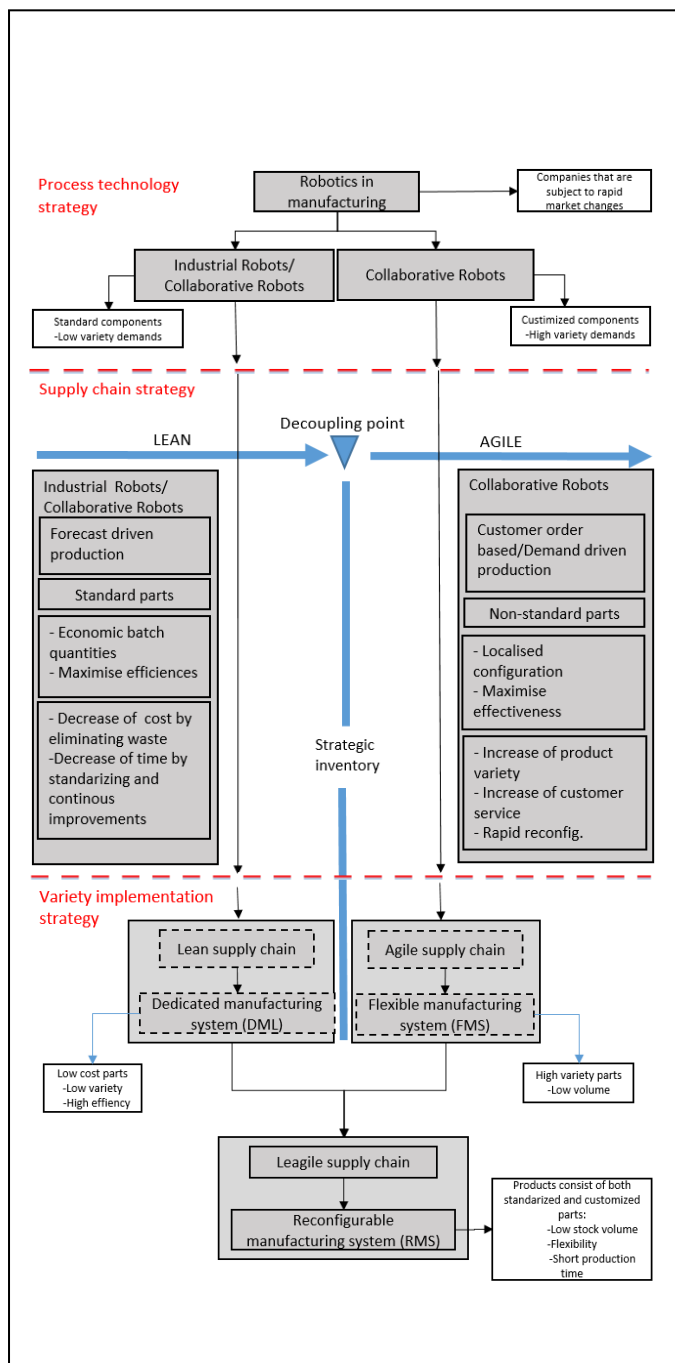
Table 3-1. Characteristics of collaborative robots.

Table 3-2 below summarizes the characteristics of the Reconfigurable Manufacturing System (ref. figure 3-3), along with reference to the relevant literature.

Reconfigurable Manufacturing System	Integrating collaborative robots into production line.	Reference sources.
Characteristics of RMS	Integrating the collaborative robots due to RMSs following characteristics: <ul style="list-style-type: none"> <li>• Modularity</li> <li>• Convertibility</li> <li>• Customization</li> <li>• Integrability</li> <li>• Diagnosable</li> </ul>	(Elmaraghy 2006), Literature (Bi et al. 2008), Literature (Mehrabi et al. 2002), Literature (Interview 2, 10.2.2), Interview
System-level	On system level RMS consist of modular SW- and HW components: <ul style="list-style-type: none"> <li>• HW: cobots</li> <li>• SW: Control system</li> </ul> The modular cobot-cells further to be arranged in serial-, parallel or hybrid configurations.	(Elmaraghy 2006), Literature (Bi et al. 2008), Literature (Mehrabi et al. 2002), Literature (Interview 2, 10.2.2), Interview
Machine-level	<ul style="list-style-type: none"> <li>• Modular HW and SW components</li> <li>• Compatibility between components</li> <li>• Compatibility between components and the product-family</li> <li>• Components to be convertible due to rapid change over from one product in the family to another</li> <li>• Modules gives the system possibility to become diagnosable</li> </ul>	(Elmaraghy 2006), Literature (Bi et al. 2008), Literature

Table 3-2. Characteristics of Reconfigurable Manufacturing System.

In this paper, the focus is on the **process technology** which is one of the strategic decisions on HOW to implement the chosen variety. Figure 3-4 below describes the conceptual framework for how to enable leagile manufacturing by using collaborative robots as a process technical strategy, and by this shows how to implement the product variety across the supply chain, including the manufacturing processes.



**Figure 3-4.** Conceptual framework for enable leagile manufacturing by using collaborative robots as a process technology strategy.

The implementation of high product- and process variety is accomplished by integrating collaborative robots with leagile manufacturing principles. The framework shows how collaborative robots, as a flexible workforce with the ability to handle dynamically changing demands, by rapid reconfiguration and human-robot task-sharing, makes it possible to deliver high variety with least costs and disturbance of the manufacturing system. Moreover, the framework also shows how the decouple point concept can be used to establish a leagile strategy, to enable flexibility and quick configurability with least costs by the collaborative robots. Further producing per the Reconfigurable Manufacturing System's part family, with flexibility, low stock volume and short production time.

The literature show that collaborative robots are implemented in industries with high variety. They are flexible in production to quickly reconfiguration when new requirements, low set-up cost and deliver high product variations (Scott Fetzer 4.1.1), (Continental 4.1.3), (Cooperation human-robot 4.1.5), (Kruger et al. 2009), (PWC 2014).

#### 4. Conclusion and outlook

Discussions on how collaborative robots fit into established supply chain strategies (i.e. lean, agile, leagile) are currently lacking from the academic literature. This motivated the study at hand, and the development of the conceptual framework presented here, to show how collaborative robots contribute to leagile manufacturing. The framework describes how to enable leagile manufacturing by using cobots as a process technology strategy, and by this shows how to implement the product variety across the supply chain, including the manufacturing processes. Given the limited discussion on the topic, the framework development is carried out by exploring literature and case examples provided in the literature and media, and complemented with semi-structured expert interviews. Therefore, the findings need to be further validated, by implementation and testing in real-life contexts. Furthermore, multiple tests are required in order to generalize (and redefined if needed) the framework provided in this paper.

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