Framework for Product-Mix and Changeover Manufacturing Flexibility

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Abstract

Facing new challenges and more uncertainty, manufacturers see the need for flexible solutions and the need to strive to achieve flexibility. However, flexibility is still not well understood and no unambiguous understanding of flexibility exists. The paper first summarizes the state of the field of flexibility, exploring different definitions and understandings of the flexibility concept from the literature. A framework for measuring flexibility performance is developed for use in measuring and monitoring manufacturing performance for handling product-mix and changeover. Additionally, a framework for integration of manufacturing systems with unreliable machines having quality issues is suggested to serve as an input to flexible manufacturing decision support. This should enable maintenance systems that are adaptive and flexible to changes in manufacturing.

Keywords: *quality; product-mix; changeovers, flexible manufacturing*

1. Introduction

Manufacturing industry today is facing many new challenges; challenges that cannot be met by applying traditional strategies of high quality alone. Challenges like smaller lot sizes, increased design variety, demand fluctuation, shorter product life cycles and rapid introduction of new technology. The uncertainty facing manufacturers is constantly increasing. To deal with these and other new challenges manufacturers have to be more flexible. Norway is a country with very high labor cost which calls for a high degree of technological innovation to produce quality products at competitive prices and with a high degree of flexibility.

Several researchers have proven the benefits of flexibility. It has been found that there exists a significant positive correlation between manufacturing flexibility and financial performance. Gupta and Elsayed explained the intensity of the global competition to develop new products in shorter time with high reliability and overall quality. [1] [11] Despite this, the field of flexibility and its relation to product quality is not a very well understood area. No universal understanding exists and researchers seem to be divided in the question of how flexibility is obtained, described and measured and its relation to manufacturing system quality and maintenance.

Regarding maintenance, the relationship between obtained product quality and machine status in operation has previously been emphasized by Chen et al. who presented a framework for maintenance planning for multi-station manufacturing processes. [2] Maintenance of manufacturing processes is a multi-disciplinary subject that combines reliability, scheduling and optimization. A framework to manage maintenance and flexibility in manufacturing should be able to support the user in the production modeling activity, feeding the decision support tools with the required data, considering flexibility as a requirement in the knowledge management framework i.e., the model must be adaptable in order to describe the many different production system scenarios, process and product flexibilities. Integrating flexibility measures which serve as an input back to the production system could help a manufacturing facility to operate in a Just-In-Time (JIT) environment. Regarding the integration of information, Kimura proposed a framework for product and process from a virtual manufacturing viewpoint. [3] Thibault *et al.* presented *Ontoforge* to support the integrated design in forging processes. [4] Bernard *et al.*, proposed a meta model structure to link the function to external conditions. [5]

This paper seeks to better study the concept of flexibility, propose a way to measure it for a manufacturing system and understand the relationship behind handling a product-mix and changeovers by a manufacturing system and the product quality.

2. Flexibility in Manufacturing

The literature presented below is not meant to be exhaustive. Instead, it is a summary of some important papers in the area. A large amount of research has been done on the topic of flexibility over the years. The concept was according to Sethi and Sethi [6] identified as early as 1921 by Lavington [7]. Throughout the century, the concept was discussed by various authors in several different contexts. The two main fields of research that dealt with flexibility were economic and organizational research. Flexibility in the context of manufacturing was first introduced by Diebold [8]. In the 1980's the subject of manufacturing flexibility really blossomed with the proliferation of the Flexible Manufacturing Systems (FMS) and other advances in manufacturing technology. The subject is also closely connected with the evolution in the microprocessor technology which has enabled new methods of production planning and machine control as pointed out by Sethi and Sethi [6]. These new methods have enabled developers and manufacturers to build features into their systems that make new, flexible manufacturing solutions possible. Flexibility has been considered as a step to manufacturing excellence (Olhager [9]). A couple of good review articles try to summarize the research in flexibility. (Gupta and Goyal, [10]), (Sethi and Sethi, [6]) and (Beach et al., [11]) are some of the important and most comprehensive ones.

2.1 Defining flexibility

Flexibility is a concept which is not easy to define; especially since most people have some form of understanding of what flexibility is. The concept of flexibility has been widely discussed; Sethi and Sethi [6] found at least 50 different definitions in the literature, even if some of these are imprecise and some overlapping with others. To be able to come up with a robust and precise definition of manufacturing flexibility we need to examine the reason behind wanting to be flexible in the first place. The most basic idea behind flexibility is that a greater level of flexibility gives the ability to adapt to changes, changes being for example variable demand, new products, machine breakdowns, government demands or other factors beyond the control of the organization. All of the factors listed are factors where the business does not know about in advance of them happening; hence we may characterize them as uncertain. So, adding flexibility to our manufacturing system we are taking measures to reduce the time and the cost that is required to handle uncertain events in the future. In other words, we are trying to hedge against uncertainty.

Many have tried to put this basic idea of manufacturing flexibility into a definition; Gupta and Goyal [10] define it as '*the ability of a manufacturing system to cope with changing circumstances or instability caused by the environment*', joining the definitions by Buzacott and Mandelbaum [12] and Mascarenhas [13]. This definition well explains the effect of flexibility; to cope with the change. It does not, however, take into account the price of the change which is an important factor of the flexibility. Ramasesh and Jayakumar [14] defines it as '*the capability of manufacturing system to continue functioning effectively in response to a wide range of changes in its operating environment, both internal and external.*' Upton [15] takes into account both the effect and the price in his definition; '*Flexibility is the ability to change or adapt with little penalty in time, effort, cost or performance.*' This definition also takes into account that flexibility concerns both reacting to change and instigating the change oneself. This definition gives perhaps the best understanding of what flexibility is.

2.2 The nature of flexibility

Upton's definition specifies that flexibility is the *ability* to adapt change or adapt. This is a crucial point in the understanding of flexibility. It joins the two ways to views of the nature of flexibility. On one side, flexibility is viewed as the systems possible behaviour rather than its actual performance; flexibility must then be viewed as a property that is inherent to the manufacturing system. This separates flexibility somewhat from most other variables of manufacturing which are usually indicators of the performance shown by the system, rather than the possible performance of the system. On the other hand, stating that flexibility is the ability implies that we know how to use the flexibility resources in the system. How well we are able to utilize the flexibility of the system may perhaps be called flexibility performance. The distinction between these is an important one, and is treated by authors like Slack [16] who separates flexibility into 1) the cost of making the change [between states of a manufacturing system], and 2) the cost of providing the capability to make the change.

As pointed out earlier, flexibility is a complex concept. There exists a strong tendency in the research community of thinking that flexibility cannot be considered as a measure in itself. Rather the concept of flexibility must be divided into several types of flexibility or dimensions. These dimensions can be seen as different areas that it is possible to be flexible within. Some have categorized flexibility; and others have suggested taxonomies with many different types of flexibilities. An early attempt to illustrate the different categories or dimensions or dimensions as he calls them was made by Adler [17], and is shown in Figure 1 and sums up (Browne et al. [18], Gerwin [19], Jaikumar [20], Mandelbaum [21], Buzacott, [22]). What is interesting to see that some of the categorizations are very similar. Later, others have elaborated and built upon these categorizations or made up their own e.g., Sethi & Sethi [6], Vokurka & O'Leary-Kelly [23]; Beach et al., [11] ;Saleh, et al.[24]).

Many authors have tried to develop taxonomies that identify the different types (or dimensions) of flexibility that a part of the concept of manufacturing flexibility. Most of these taxonomies are based on empirical studies, but some also try to summarize the previous literature to identify the types that are overlapping or types that are basically equal but with different names. The taxonomy proposed by Sethi & Sethi [6], defining eleven different types of flexibility is a good example of the latter. The basis of the proposed taxonomy is the work of Browne et al.[18], and it was further developed based on a thorough literature study. The study sought articles defining different types of flexibility. The eleven types that are presented is a summary of all the types of flexibility identified in the literature at the time, and the article cites around 200 previous works. The article meticulously examines each of these types of flexibilities and describes what its purpose is, by what means it can be achieved and suggestions on how it can be measured. They also show how they categorize the different types. The measures presented are measures for each individual type of flexibility. Others have taken this taxonomy and expanded it further. Vokura and O'Leary-Kelly [23] identified an additional four new types of flexibility that they added to the taxonomy giving it a total of 15 different types of flexibility.

Although the concept of taxonomies seem to have caught up on among researchers, some criticism have been raised against the attempts to make taxonomies; according to Beach et al. [11] '*the development of a generic taxonomy is likely to remain elusive as manufacturing clearly possesses both a strategic and operational dimensions.*' But as Koste et al. [25] points out: *'Given the relative infancy of the flexibilitsy measurement research, we advocate treating the flexibility dimensions individually until a greater level of understanding is reached.'*

2.3 Relations between types of flexibility

The taxonomies identify individual types of flexibility found in manufacturing facility. But for anyone who knows how intricate factories and other manufacturing systems are, it should be evident that these types of flexibility may be very likely to have some kind of dependency or relation to one another. If we want to be able to assess the flexibility of an entire manufacturing system, we should at least have some idea of what interrelations that exist between the different types. The taxonomy by Sethi & Sethi [6] suggests the structure of linkages between the various flexibility types. The first three types are flexibilities of the important components of the system. The ones in the middle, the system flexibilities are dependent upon these basic flexibilities, and the aggregate flexibilities are aggregates of the various system flexibilities. This approach of putting the various flexibilities into a hierarchy implies that the various flexibilities are somehow correlated. This again raises a challenge when we are trying to measure the flexibility.

Koste and Malhotra [25] performed a study that examined the literature which links different types of flexibility. This gives an indication of which relationships between flexibility types are the most important, and which that are located in the different tiers. Based upon this study they propose a new hierarchy which illustrates the relationships between the different flexibilities; the different types of flexibilities are grouped from what level in the business they belong to. The individual resources are at the bottom of the hierarchy, while strategic business unit is at the top. An important point here is that each level is dependent of all the levels beneath it in the hierarchy. Another point that will be discussed later is that it seems that the time horizon of the flexibilities increases with the tiers, so that the flexibilities in the lower tiers are important in the short-term time horizon and the flexibilities towards the top are important in the long-term time horizon.

Ramaesh and Jayakumar [14] have built their categorization on the realisation that different flexibilities matter in different time horizons. They sort the flexibilities into categories based upon which time horizon the flexibilities are of concern. The three categories are short-, medium- or long term time horizon. This categorization however seems intuitively wrong. Labour flexibility and machine flexibility should at least be included in the short-term category. For a comprehensive summary on the many ways to categorize flexibilities, the review by De Toni and Tonchia [26] is recommended.

2.4 Identifying flexibility

Building on the idea of taxonomies, Upton [28] have proposed a framework to further decompose each type of flexibility in the form of taxonomies into different elements. He argues that management and academics both lack a platform that makes them able to clearly define which type of flexibility is 'needed' or wanted. His framework is supposed to enable especially managers to characterize or define more exactly what they are talking about when discussing flexibility. As will be discussed later, the role of the management is an important one when examining manufacturing flexibility.

Upton's framework is made up of three questions that should be answered in the right order; dimension, time horizon and element:

- **Dimension-What are we assessing the flexibility of?**
- **Time horizon-What is the period over which change will occur? Minute by minute, days, weeks or years?**
- **Elements-Which element(s) of flexibility are most important to us? Which of the following are we trying to improve or manage: range, uniformity across the range or mobility within the range?**

Dimension defines the nature of what we want to be flexible. The dimension can be either continuous (e.g. output rate) or discrete (e.g. product models). The time horizon can be translated into one of the three following types of flexibility: operational, tactical or strategic flexibility based on the terms from (Carlsson, [27]). This division also resembles the one made by Ramasesh and Jayakumar as shown above. Three different elements are listed as the ways for being flexible. *Range* concerns the possible positions within the dimension. This could for example be the number of different products that can be processed or the range of volumes that can be produced with the current equipment. *Mobility* within the range is the second way to be flexible. An example of this may be the penalty, in form of time or coat, to switch between products in the production; flexibility increases as the penalty decreases. *Uniformity* is the ability to maintain the value of a performance measure (e.g. quality or cost) within the range.Using this framework mangers or scientists would be able to pinpoint in an unambiguous way which type of flexibility that is being discussed.

This model was further elaborated by Koste et al. [25] who proposed a new element in addition to the three proposed by Upton; range-heterogeneity relates to the heterogeneity of the options from the range-number (called range by Upton). They then continue to exemplify these four elements for ten dimensions (types) of flexibility; machine, labour, material handling, routing, operation, expansion, volume, mix, new product, and modification flexibility. In a later study the same authors use this proposed model to thoroughly measure flexibility at several manufacturing facilities.

2.5 Product-mix flexibility

Bengtsson [37] provides an overview over the different understandings of the concept of product-mix flexibility. He also points out the three main aspects that can be drawn from the list:

i) **The ability to switch quickly between products with a given product mix**
ii) **The ability to handle changes in relative volume among the products within a given product mix**
iii) **The ability to handle design modifications and expand the product mix**

After examining these we find that they coincide well with the concept of flexibility described by Slack [16] quoted by Gupta and Goyal [10]. This understanding is now described further.

If we examine the product-mix flexibility in the light of the model by Koste et al. [25] shown earlier, we see that their mix flexibility is found on Tier 3. Here it is dependent on all the flexibility types found in tiers 1 and 2:

-Machine flexibility
-Labour flexibility
-Material handling flexibility
-Routing flexibility
-Operation flexibility

These flexibility types can be viewed as subtypes of the product-mix flexibility, and they all affect the product mix flexibility. A method that tries to assess all of these subtypes and the combine the results into one aggregate measure for the product-mix flexibility could be used, but would require substantial work. What would be more reasonable is finding a method of measurement with which one is able to measure the product-mix flexibility, and where these subtypes are implicitly embedded would be more effective, and presumably more easily understood.

Several studies have also treated the impact of product-mix flexibility and its relationship with other flexibility types. Salvador et al. [38] found that product-mix flexibility and volume flexibility in some cases have a negative effect on each other whilst in other cases may have a synergetic relationship. Yang et al. [39] found that design for manufacture (DFM) affects the product-mix flexibility. Hutchinson and Das [40] lists the following as capabilities to achieve product-mix flexibility: manufacturing processes with wide range, workforce flexibility, quick changeover times and the ability to introduce new products quickly.

As pointed out, Slack [16] quoted by Gupta and Goyal [10], presents maybe the best understanding of flexibility in the context of this chapter. The basic concept behind this understanding is the idea that flexibility is regarding the changing between states in a manufacturing system. The size of the ranges of states that the system can adopt along with the ease of state changing determines the flexibility of the system. The wider the range of states and the smoother the changes between the states, the more flexible the system is regarded to be. The states could for example be a systems ability to make a wide variety of products, manufacture different volumes or quality levels.

The cost element of a system's flexibility is by Slack distinguished on the basis of:

(1) **The cost of making the change**
(2) **The cost of providing the capability to make the change**

Here the first cost is actually what determines flexibility, while the second is only the price you pay to achieve that flexibility. This means that after having bought the equipment; its abilities and how one exploit them is what determines the flexibility. This is supported by McLntosh et al. [41] who conclude that '*An improved flexible manufacturing capability does not make a business more competitive. Rather, it is how this capability is used […] that will give the business a competitive advantage* '.

Slack distinguishes the cost of moving from one state to another and the time it takes to do the change. He states that the time and the cost are inversely related; the time it takes can be reduced at a certain cost, and the cost can be reduced by increasing the time it takes to make the transition. This statement obviously distinguishes between the direct cost of the change and the cost of the time, in most cases, the time used to make the change also represents a cost, like the example of a changeover where the production system is not producing anything during the time of changeover and this time can be seen as a cost in itself.

On the basis of this, Slack defines the three dimensions of flexibility:

(1) The range of states the system can adopt
(2) The cost of moving from one state to another
(3) The time necessary to make the transition

Following this reasoning it is clear that in order to monitor flexibility there are two key elements. The first element is monitoring the costs related to the changeovers between the products or product families. In many cases, various products belonging to the same product family can be produced on the same setup, and in that case it may be more fruitful to monitor according to the product families.

The second factor is the time that is used for the changeovers. The time is a factor since it affects the capacity of the system. A short changeover time will have a little effect on the capacity, while a long changeover time will leave the system unusable for a longer time, and reduce the total capacity of the system.

The third dimension that is mentioned is the range of states that the system can adopt. While this of course is an important measure, in the light of this chapter it is perhaps less useful. Expressing it in another way may make it much more descriptive in this case; 'the range of relevant products produced by the organization that the system cannot process'. In this case where we are talking about flexible assembly lines, knowing the number of products that needs final assembly outside of the assembly system can be more interesting than knowing the theoretical range of products that can be processed in the system. Alternatively this could be expressed by the percentage of products that can be processed by the system. The range is not however a key factor to the day-to-day flexibility but should still be included into the framework since it plays a role when assessing flexibility in a longer time perspective. The range dimension is probably part of what was categorized as medium-term or long-term time horizon by Ramasesh and Jayakumar [14]. The cost and time on the other hand are important in the short-term horizon.

Although this is Slack's general view of flexibility it matches very well with what has been described as product-mix flexibility. Different authors have also suggested measures for the product-mix flexibility. Ramasesh and Jayakumar [14] list several of them. Brown et al. [18] and Gerwin [42] suggest *the number of different part types that can be produced* as a measure. This can be seen as the same as Slack's dimensions called *range*. Wernecke and Steinhilper [43] suggest *the changeover cost between known jobs within the current production plan* as their measure. This measure can be seen as Slack's flexibility dimension *cost*. Jaikumar [14] suggest that *the expected value of a portfolio of products for a given set of contingencies* should be used as a measure for the product-mix flexibility. This measure is not directly relatable to Slack's understanding of flexibility. It can be seen as a result of the flexibility rather that the flexibility performance in itself.

Others have applied more complex methods of measuring the product mix flexibility. Wahab [44] and Bateman [45] both use complex mathematical equations to assess the flexibility. The problem with both of these methods is that they are perhaps overly complicated and too theoretical by nature to be applied to a real manufacturing system with ease.

The author believes that Slack's understanding of flexibility provides a basis that is easy to understand and to work with while at the same time expresses what seems to summarize what is the general understanding of product-mix flexibility. It gives a foundation upon which it is possible to analyze the flexibility performance of a manufacturing system by looking at the most important variables: time, cost and range. The use of this understanding of flexibility also conforms relatively well with the definition discussed earlier. The definition says that '*Flexibility is the ability to change or adapt with little penalty in time, effort, cost or performance.*' Comparing this to the basis provided by Slack we can see that it fits well. A decrease in cost or time of making a state transition is obviously a decrease of the penalties. An increase in range can be seen as an increase in the ability since it increases the number of products that may be processed on a system with presumably lesser penalties.

What is important is to realise the fact that the three dimensions may have a different importance in different businesses. In a manufacturing facility with excess capacity the time is not as important, but the cost is more important. In a facility with a more limited capacity (more capacity constraints), the time may matter relatively more. This is why an assessment of the relative importance of the categories must be done in advance. Other aspects that need to be considered are the level of detail on the measuring and the frequency of measurement. The level of detail chosen by the business will depend on several factors which will be different in different businesses. The resource requirement for doing the measurement is perhaps the most important factor. If the business has a MES that harvests data automatically with a great deal of detail, using this level of detail would of course be ideal. If on the other hand a person is needed to manually do the measurements, the level of detail chosen will be lower. The advantage of having quality data with a high level of detail is quite obvious; it will give a better view of exactly what can be improved and a better understanding of which actions should be taken. It would also give an assessment of how good the actions for improvement are working. The frequency of measurement is also a decision the business must make. The measurement frequency depends largely on the same factor as the level of detail; the resources needed to do the measurement. If it is expensive to do the measurements, they will be done less frequently. When it comes to frequency it should be noted that it does not have to be constant. After having done actions to improve flexibility it will be interesting to increase the frequency of the measurements to better be able to assess the effect of the actions.

Cost component

The cost of the change, first and maybe the most important of the key elements, is measured through monitoring and data gathering in the manufacturing system. In order to best analyze the cost, a breakdown of the total changeover cost is interesting.
Below is a cost of operation that are generally performed during a changeover. Obviously not all production systems include all of these, and other may include other beyond the list.

- **Planning and initiating the change in e.g. planning system**
- **Moving and instructing personnel**
- **Personnel waiting for new production to start**
- **Reconfiguring manufacturing system**
    - **Changing tools in machines (retooling)**
    - **Changing program on machines**
    - **Changing tools on robots**
    - **Changing program on robot**
    - **Changing pallets etc.**
    - **Changing programs etc. on other equipment**
- **Getting parts/raw material for new production**
- **Removing parts/raw material from previous production batch**

All of these activities have a certain cost related to them. Even so, many manufacturers do not do analysis at such a low level.

Included in the costs of a changeover is also the cost of the time used which can also be broken down into:

- **Cost of lost production time**
- **Cost of ramp-up time (new production is not starting at 100% effectiveness)**

Time component

Apart from the fact that time is associated with a cost, the time itself is an important factor. By time we understand the time that the system is unavailable for operation. The time used for changeovers affects the cycle time for the products, and hence reduces the capacity of the system for a given product mix. Olhager [9] provides an excellent overview of the benefits that can be gotten from setup time reduction (changeover time),with RMI = raw materials inventory, WIP= work-in-progress, FGI=finished goods inventory.

The times needed in the measurement are the following:

- **Changeover time (time from the production of one product is finished until the production of the next commences)**
- **Ramp-up time (effective time lost from start of production until production is at 100% effectiveness)**
- **Shut-down time (effective time lost from system is at 100% effectiveness until system is completely stopped)**

The time components included in a changeover are illustrated in Figure 1. The process consists of a shutdown time where the system goes from 100% effectiveness to full stop, the actual changeover time and a ramp-up time. The shut-down and ramp-up are as illustrated often gradual, although they may also be virtually instant, meaning that the system is either operating at 100% or it is completely stopped. The 100% effectiveness does not mean full capacity, since manufacturing systems rarely run

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at maximum capacity. The 100% effectiveness rather means that the system is running at 100% of the planned capacity.

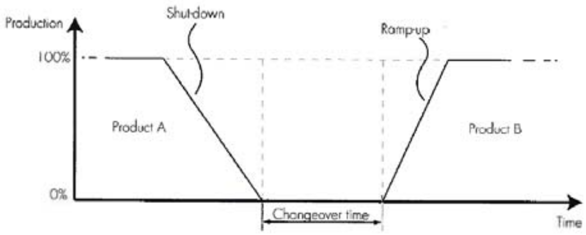

Figure 1 Illustration of changeover time

In many cases the ramp-up (t_{RU}) and shut-down (t_{SD}) times can be estimated with the simple formulas, where we assume that the ramp-up/shut-down is linear (as shown in Figure 8):

$$t_{RU} = \frac{T_{100\%} - T_{0\%}}{2}$$

$$t_{SD} = \frac{T_{0\%} - T_{100\%}}{2}$$

Here, $T_{100\%}$ is the time at which the system is producing at full capacity and $T_{0\%}$ is the time at which the system is completely stopped. If the shut-down and/or ramp-up times are long, or if the system clearly does not have a linear ramp-up/shut-down, this estimation is not applicable.

Range component
It highlights to which degree we are successful in having a flexible assembly system that accommodates the product range of the business. It may give insight into which products or product families to prioritize in further development of the manufacturing system.

The monitoring of the range aspect over time is especially important. If the number of products that cannot be assembled on the line increases it may indicate that we are introducing new products that are not sufficiently adapted to the manufacturing resources, and that more efforts should be put into manufacturing considerations during product development.

3. Framework Overview

3.1 Initialization
The initialization phase consists of several steps that are necessary to perform before using the framework. The activities here are mainly used for individualizing the process to the manufacturing system being analyzed. The assessment consists of a more quantitative evaluation of the company's flexibility and their strategy in relation to flexibility.

Based upon the assessment, some indicators are devised. These indicators are later calculated at each measurement. The use of these indicators makes it easier to monitor the flexibility without having to analyze the lower levels. The indicators should be devised so that they fit the individual business and their manufacturing process.

These indicators are devised in such a way that the strategy of the business is taken into account. The strategy of the business according to the three dimensions, time, cost and range is evaluated. When the assessments of these three are to be translated they are valuated according to how important the business considers them to be.

The main part of the initialization is the assessment using the two methods by Gupta & Somers and Koste & Malhotra. In addition to these methods a method to value the dimensions according to strategy is needed. Another and maybe equally important effect of having management doing these surveys is the fact that it puts focus on flexibility. The role of the management is an important one in when it comes to the flexibility of a business. By involving the management through the entire organization, they get a personal ownership to the strategy of flexibility.

3.2 Measurement
All the elements that should be measured are shown in Table 1, Table 2 and Table 3. These should be measured for all products or, if the products in each family are sufficiently similar, for each product family. Measuring for each product family could also be appropriate if the number of products is very large, which would make the measuring itself extremely costly.

The elements in Table 1 are the elements in the cost category. This is the major category, and perhaps the most important one. These elements describe the costs of all the activities involved with making a changeover. Many manufacturers have a quite good overview over these costs, at least on the category level, but not on such a detailed level as here. As is discussed below, it is not necessary to measure at this level of detail all the time.

Table 1 Cost elements to be monitored

Category	Elements	Remarks
Administration	Planning changeover	In e.g. MES-system
	Executing changeover	Taking the steps to initiate the change
Personnel	Moving personnel	Moving people from other locations or jobs
	Instructing personnel	
	Personnel waiting	Personnel waiting for system to get ready
	Personnel clock-in	Clocking in and other misc. actions
Reconfiguration	Retooling machines	Changing tools on machines
	Reprogramming machines	Changing programs and doing set-ups of machines
	Retooling robots	Changing tools on robots
	Reprogramming robots	Changing programs and doing set-up of robots
	Changing pallets etc.	
	Changing programs on other equipment	Changing programs and set-up of robots
Set-up and clean-up	Fetch parts / materials from stock	
	Prepare parts/ materials	Put the needed parts or materials in its proper place (rack, container etc.)
	Return unused parts/materials to stock	

Table 2 Time elements to be monitored, entire system

Element	Remarks
Total changeover time	Time from system is stopped until it is started again
Ramp-up time	Time lost on system because of ramp-up
Shut-down time	Time lost on system because of shut-down

Table 3 Range elements to be monitored

Element	Remarks
Number of items not processed on system	The number of relevant products that are processed on other systems
Number of items processed on system	The number of products that can be processed on the system

3.3 Benefits

Accounting support
In pricing and cost accounting it is important to know the different cost components related to the product, using the framework one gets in-depth breakdown of the costs related to manufacturing. This enables the accounting department to better calculate the prices of new products and orders. It also gives a better understanding of the cost structure when doing cost accounting, an important tool in analyzing the economic performance of the business.

Graphic representation
Along with more specific reports, graphic representations of the flexibility performance may possibly be quite useful. If the integration of the framework allows it, representing the flexibility on the dashboard is a good solution [31]. This could have a value on different levels of the organization. On the top level, typically top management and board, the flexibility would be an indication on how well the manufacturing is achieving the strategic goal in a long time horizon (assuming the strategy is increasing flexibility performance). For the manufacturing management it may be a day-to-day monitoring the performance.

Decision support
Strategic decision support is one of the important benefits that can be derived from the framework results. It can be imagined that the results from the framework can be used for support in several key strategic decisions. Examples may be prioritizing of costs cutting efforts, assessment of investment options in comparison with present equipment and several others.

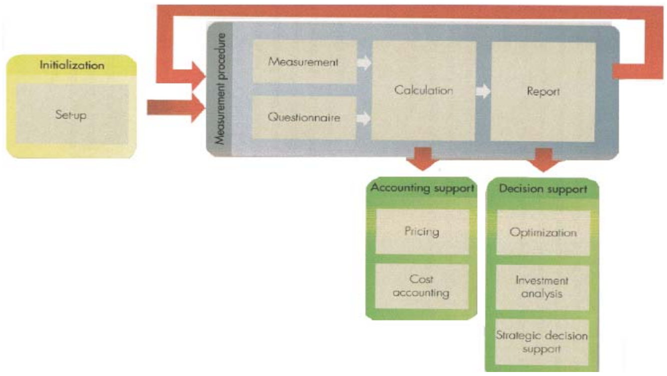

Figure 2 A quality framework for product-mix and changeover flexibilities

Monitoring using the framework

The most important use of measurement is probably monitoring over time. The framework as it is will not provide much useful information until it is used for monitoring over a period of time, either continually or more realistically at certain time intervals. This will provide a valuable overview of the development of cost components and changeover time improvement. It is not necessary to measure all the elements each time a measurement is done. The lower level elements may be included only on every two or three measurements that are done. The top level elements however should be included in all of the measurements.

The questionnaires are a part that does not need to be done as often as the measurements. They will not give a realistic view of the development of flexibility is used often. Probably, answering the questionnaires every six months or maybe once every year may be more than enough to get good results.

Integration

How a system like this is integrated is an important factor of its success. Advances in information technology have made it possible to integrate a system of measurement into the manufacturing system in a way that has not been possible earlier. The data acquisition capabilities of manufacturing execution systems (MES) in particular would be a great combination with the framework. Integration with MES would also facilitate integration further up the enterprise resource planning system (ERP). Another technology that could be useful in integration is RFID. The RFID tags could be used throughout the manufacturing system to automatically track resources. This would make possible to automate harvesting of data, and lower the operating costs of the framework.

On the other end of the scale, the integration could be done with very simple tools. If the measurement frequency is low and the amount of data is relatively small it would be more appropriate to integrate the system in a spreadsheet like Microsoft Excel or in a scripting language.

Flexibility improvement

After having decomposed the costs and times involved with changeovers in a manufacturing facility, several factors can be identified that may contribute to flexibility improvement. Component feeding to the system is one of the factors. It is a major contributor to the cost of changeovers. By reducing the cost of component feeding the flexibility performance may be significantly improved. This can in many cases be achieved integrating new automated solutions of component transport and feeding. Another major contributor to the cost of changeovers is related to personnel. In a country like Norway with extremely high labour costs it is essential to reduce the involvement of humans, and even more important to reduce the idle time which often occur during changeovers and personnel movement. To counter this there are several actions that may be taken. First cross-trained workers than can perform several tasks will reduce the need for personnel movement. The workers may also be trained to do the work needed for the changeovers themselves. Thirdly it is obvious that reduced changeover time may reduce idle time if some of the workers are not involved in the actual changeover.

Having equipment that is able to handle multiple products or multiple product families is also a strategy for increasing flexibility. Making equipment that can accommodate as many products as possible on the same setup obviously decreases or eliminates both the time and the cost of changeover between these products. This action falls into the category of providing the capability of flexibility as described by Slack. It does however make the system less flexible as to change to whichever product if the setup does not accommodate all products. This way of thinking of course does not only apply to the development of the system itself, but just as importantly it is important to the development of the products themselves. The use of design for manufacture (DFM) or design for assembly (DFA) has been cited as one important enabler for product-mix flexibility. [44]

Measured by survey (direct subjective measurement)

The parts of the framework described above consist of direct objective measures, quantitative measures. In addition to these quantitative measures, the framework contains some qualitative measures in form of questionnaires that should be answered by management on different levels of the organization.

Desired properties

For a measurement of this kind there are a number of properties that can increase the quality of the measure and make it better and more usable. Some properties are essential, while some are important although not critical to the result.

Essential properties:

- *Valid*
- *Eclectic*, meaning it should be valid over time and ideally be compatible with future technology developments.

Important properties:

- *Robust*, in the same sense that it should be usable in different settings.
- *Transparent*, meaning that it should be fairly easy to understand how it is calculated and to review different parts of the calculation.
- *Easily understandable results*

Making sure that the measure is valid is arguably the most important but at the same time perhaps the most difficult among these. As Churchill [60] puts it; '*construct validity […] lies at the very heart of the scientific process*'. Making sure that the measure is a valid one means that it actually tells what it is supposed to tell. Reaching a valid measure is a meticulous back-and-forth process which includes considerable statistical work. The procedure cited in many of the works on flexibility measurement is the article by Churchill, which introduces a '*paradigm for developing better measures of marketing constructs*'.

Measuring using the framework by Koste et al.

The framework developed by Koste et al. is based on their work by Koste and Malhotra from 1999, in which they introduce a model where they separate flexibility into four dimensions rather than three. This four dimension model to measure six types of flexibility:

- Machine flexibility
- Labour flexibility
- Material handling flexibility
- Mix flexibility
- New product flexibility
- Modification flexibility

For each of the types of flexibility, all four dimensions (range-number, range-heterogeneity, mobility and uniformity) are measured. This results in a total of 24 scales. The measurement is done through questionnaires with a series of questions for each scale. In total 122 questions were to be answered in the form of a Likert scale. The questions were to be answered 'relative to your major competitors' to account for the relative nature of flexibility.
Data was collected from 158 businesses and the results were statistically analyzed. After analysis 18 of the questions were dropped. The results were all compared to one single question asked together with the questionnaire: 'rate the overall flexibility of manufacturing in your plant' on a Likert scale from highly inflexible to highly flexible. From this it was found that businesses that regarded themselves as flexible also scored higher in the rest of the scales.

Measuring using the framework by Gupta and Somers

The framework developed by Gupta and Somers is quite similar to the one by Koste et al. in the way that they are both based on a questionnaire. The framework has fewer questions than the one by Koste et al. and it measures more types of flexibility. The types of flexibility measured are:

- Volume flexibility
- Programming flexibility
- Process flexibility
- Product and production flexibility
- Market flexibility
- Machine flexibility
- Routing flexibility
- Material handling flexibility
- Expansion and market flexibility

The method originally consisted of 34 questions but after analysis the number was reduced to 21.The number of questions related to each type of flexibility can be seen in the parentheses in the list above.

Criticism

As mentioned earlier this framework is made up of what De Toni and Tonchia [26] categorize as indirect measures. These are measures that measure the characteristics of the system which allow for flexibility. Both qualitative and quantitative measures are used in the framework and in this way it is more robust.

The main feature and perhaps the main strength of the methodology is it simplicity. The methods use data which is in most cases already available in businesses. The time and cost of changeovers is something which most manufacturing plants monitor. The difference here is that the framework suggests a more thorough breakdown of the components in time and cost, in order to better pinpoint the areas with room for improvement. The fact that the framework allows for different levels of detail and different frequencies of measurement gives it an adaptability that will ensure that it si possible to integrate into most businesses.

The method does integrate most of the flexibility types suggested by among others Koste & Malhotra and Sethi & Sethi as the basis for the product-mix flexibility. The flexibilities that are maybe not as well integrated into the framework are the routing flexibility and the volume flexibility. This may be seen as a clear weakness of the framework.

Another weakness of the framework is the fact that it does not take capital cost into account. Neither the capital cost of work-in-progress (WIP) nor the capital cost of the system itself is taken into account in the framework. The cost of the system itself can be seen as what Slack calls 'the cost of providing the capability to make the change'. The framework only looks at the penalties related to the change itself, or what can be regarded as the 'flexibility performance'. The cost of the work-in-progress on the other hand, should perhaps have been included in the framework, since the level of flexibility presumably affects the level of WIP. The WIP can be seen as a result of the flexibility rather than the flexibility itself. Work in progress of course may be and in many businesses is monitored, but it is difficult to relate to any changes in the overall WIP to one specific cause. There are many factors apart from flexibility that may affect the level of WIP in a manufacturing system. Yet another factor that is not taken into account is the reliability of the system which could affect the flexibility.

The framework is intended to be used on one subsystem only; in this case the assembly system. It would be desirable to be able to apply the framework to an entire manufacturing plant. The framework could be used for this by using it individually for all of the subsystems that of interest. This will hive data on which subsystems that are showing the most improvement in flexibility, but it does not provide a way to compare the flexibility of the different subsystems. This is partly due to the nature of flexibility, and the fact that all the subsystems have different characteristics.

It is worth noting that Hallgren and Olhager also cite changeover time reduction as a major contributor to volume flexibility. This suggests that the different flexibilities are indeed interrelated, and that it is very difficult to separate one from another. This is also one major obstacle in the pursuit of a general measure for flexibility instead of measures for the individual flexibility types.

The goal of this framework was providing an easy to use, and easy to understand way of measuring the flexibility of a subsystem in a manufacturing plant. The proposed framework does exactly this. Some sacrifices have been made in order to keep the framework as simple as possible. This has led to some shortcomings, but these should not affect the results of the measurement even though they may lead to somewhat less understanding. The framework returns an economic value of the flexibility performance in a short-term time horizon along with the time penalties and the range of the system.

5. Summary

Even though much understanding of the concept has been developed, no real conclusions on how to treat flexibility exists. This will most likely continue to be a challenge in the future. The way flexible capabilities are utilized, and how they are implemented is of utmost importance to its success. An investment in equipment with flexible qualities should be supported by an articulated strategy of flexibility, and serious efforts to improve the flexibility through efforts like cross-training of personnel, changeover time reduction and others.

The goal of developing a simple framework was achieved, although not yet tested. Testing the frameworks is the next step. The framework has some weaknesses, but the value of its simplicity should outweigh these.

Some of the additional areas of potential research are

a) Understanding quality in relation to Inspection and Rework

For expensive products or products requiring many hours of processing, it may sometimes make economic sense to rework a product rather than discard. An example of such a rework loop is shown in Figure 6. For such a process, it may be of interest to determine the optimal location of the inspection booths, so as to maximize average production, while maintaining risk within acceptable limits.

b) Risk Management Framework

By estimating throughput distribution of a manufacturing system, the risk associated with a given system for a known demand can be obtained. Also, through segmentation, the throughput distribution at the end of each segment of a serial manufacturing system can be achieved.

c) Identifying Risk Critical Segment

Using the proposed approach for estimating throughput, it is of interest, to evaluate the risk associated with each segment of a manufacturing system. Further, using this information, risk critical segments of a manufacturing system can be identified. Developing a risk management system, capable of reducing and redistributing risk from the risk critical segments, could lead to an increased and more consistent throughput.

d) **Mitigation of Risk**

Risk mitigation is the process of reducing risk associated with a system. By identifying the critical segments and maintaining the critical machines, the risk associated with a given segment can be reduced. As shown in Figure 7, preventive maintenance pushes up the overall probability distribution of throughput for a given segment by improving the condition of a machine, and reducing its likelihood of failure over the coming intervals

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