



**KTH Industrial Engineering  
and Management**

# Evolvable Production Systems: Demand Responsive Planning

HAKAN AKILLIOGLU

Licentiate Thesis

School of Industrial Engineering and Management  
Department of Production Engineering  
The Royal Institute of Technology, Stockholm  
NOVEMBER 2011

TRITA-IIP-11-12  
ISSN 1650-1888  
ISBN 978-91-7501-167-7  
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Department of Production Engineering  
The Royal Institute of Technology  
S-100 44 Stockholm

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# Abstract

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Dynamic and unforeseeable characteristic of the current market and production environment is not feasible to be met through pre-set parameters being dependent on the predictions. Handling this matter requires to keep focus on production system adaptability. Evolvable Production System has achieved fully system reconfigurability through process oriented modularity and multi agent based distributed control system architecture. One of the essential enhancements provided by EPS on the shop floor is achieving minimized/eliminated system setup time in response to changing product requirements.

Manufacturing planning and control system, on the other hand, follows hierarchical principles which are quite much reliant on the predicted information so to structure production and planning environment on it. Production system limitations, such as lack of adaptability in response to changing conditions, are in fact influencing the planning system to be structured on the predictions. The enhancements which are ensured by the architecture of EPS enable to relax the constraints on planning system which are imposed by the limitations of production system. These enhancements have an effect at different levels in the planning hierarchy. On the light of these improvements, the planning framework as it is used so far in the industry becomes invalid and this arise a requirement for planning system structure to be designed according to a fully reconfigurable system to be able to benefit such a production system by all means.

This thesis targets to enlighten the relation between the production system characteristics and planning system structure by emphasizing the planning problems and proposing a planning reference architecture solution to be able achieve a responsive planning framework.

# Acknowledgements

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First and foremost, I would like to express my gratitude to my supervisor, Prof. Mauro Onori for all the expertise, leadership, time and patience. He has always made available his support and help. I would like to thank him by all means for his positive and friendly attitude.

I am indebted to my colleagues for their constant back-up, encouragement and help throughout my studies. Special thanks should be given to Kerstin Dencker, Daniel Semere, Antonio Maffei, Pedro Neves, Joao Ferreira and Marcus Bjelkemyr.

I am grateful also to all the members of the EPS group for their support and cooperation. Special thanks go to Prof. Jose Barata, Luis Ribeiro, Dr. Christoph Hannisch, Andreas Hofmann, Dr. Niels Lohse and Dr. Piero Larizza.

The most exceptional thanks from the very bottom of my heart go to my eternal friends in Sweden for their support and intimacy. I will not name all of them being afraid to miss one. I cannot imagine a life in Sweden without their friendship.

Finally, words alone cannot express the thanks I owe to my family for their boundless love, support and compassion.

Stockholm, November 2011

HAKAN AKILLIOGLU

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# List of Publications

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- 1) "Evolvable Assembly Systems - Mechatronic Architecture Implications and Future Research"  
Akillioglu H., Neves P., Onori M.  
CATS 2010, Norway
- 2) "Evolvable Production Systems and Impacts on Production Planning"  
Akillioglu H., Onori M.  
ISAM 2011, Finland
- 3) "Dealing with the unpredictable: An Evolvable Robotic Assembly Cell"  
Onori M., Akillioglu H., Neves P., Hoffmann A., Maffei A., Siltala N.,  
CARV 2011, Canada

# 1 INTRODUCTION

## 1.1 Background

The business environment has been developing and altering by increasing the amenability of the companies in order to satisfy every single customer. It became obligatory for the companies to produce in an efficient way because of increasing customer consciousness and powerful rivals. As far as the relation between customers and companies is concerned, there is a considerable change on the effect of customers on the companies. Companies have produced and supplied goods to market as they designed and produced for long. However in today's environment the companies are targeting to obtain the capability of supplying specific products to every single customer in accordance to their wishes. At the same time production system should allow production volume to be changed without losing capability of rapid reconfiguration between products whose process requirements are diverse.

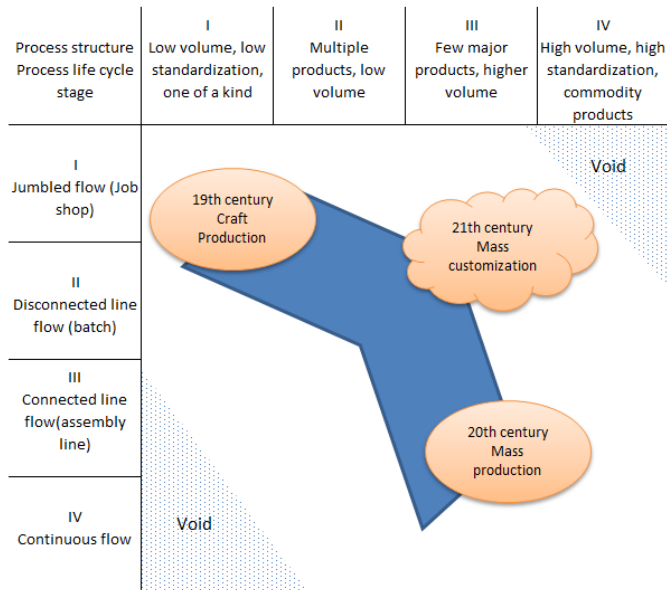


Figure 1-1 Product process matrix

Production systems target a segment in the market and processes are characterized accordingly. In the product process matrix [1] at Figure 1-1 the manufacturing processes are classified into 4. One essential outcome which can be extracted from this matrix is the prominence of the targeted market for the production system requirements. A flow line might not be feasible for high product variety and low volume production. Similarly, the effective way of low variety and high volume products is to setup a connected line flow with an operative flow of products such as a conveyor system.

The development of production systems has followed the diagonal track from upper-left corner which shows the typical characteristics of 19<sup>th</sup> century craft production to bottom-right where 20<sup>th</sup> century mass production is located at product process matrix. Technological advancements, new methods, growing use of automation in industry have enabled companies to produce higher volumes with higher quality in a cost effective way. However producing highly customized products in satisfactory volumes became a requisite to survive in industry. The production systems are aligned diagonal in the matrix which means that the systems can produce at a point between low volume-low standardization-highly customized and high volume-high standardization-lowly customized. Several studies has been conducted on this diagonal line to find the best solutions taking into account the trade-offs between volume, customization and standardization. In the center of this diagonal boundaries production systems stand. To be able to relax these constraints and to move out of the diagonal line in the matrix, the indispensable way is to develop new production systems with high reconfiguration capabilities in a short time and effective way.

From the manufacturing planning and control (MPC) point of view the focus has stayed more on the management of resources, material, workforce for best efficiency by accepting the capabilities of production system as it is. In one side the operational requirements of product and another side the available resources and capabilities of the system is standing, where the best match and use is sought to be able to meet the customer demands. The factors which are changing by time are the mainspring to update the plans of production. New products which are introduced to market, randomly arriving orders, unexpected economic problems

etc. are all needed to be handled by the planning systems of the company. At the same time the industry in which the company is acting has direct effects on the strategies.

The main actor is the production system as it can be considered as the most value adding section of the whole system from the company point of view. It plays crucial role to invest from the beginning to the right system at the right time. Many of the investments today are based upon the forecasts of the experts, assumptions of the future products and product lifecycles. In today's highly competitive market, there is no room anymore for companies to jeopardize their investments. Ever changing product characteristics, market dynamics and technological possibilities over time has forced process and production system structures to adapt new circumstances and still doing so.

## **1.2 Research Scope**

In this thesis the focus has been given to the relation between production system characteristics and the MPC systems. The planning systems are divided into 3 phases concerning their planning time horizon as long-term, intermediate and short-term. Strategies and tactics are developed in the high level planning phases whereas application and control of the decisions are conducted at the bottom level. Although planning methods can change depending on different requisites of companies, planning framework stays similar. To have a comprehensive view, it is important to take into account all phases of planning system.

Both from the MPC and EPS point of view, the detail of research can be enormously wide, however the emphasis has been given to developing the most suitable and applicable planning reference methodology which complies with evolvable production systems characteristics. The starting point of the research has been the advancements which has raised with the introduction of a new paradigm, Evolvable Production Systems [2]. Since most of the restrictions and incompetency in planning stem from the production system characteristics, considerable improvements in the production systems can invalidate the available planning methods. At this point, with the introduction of EPS, absence of a feasible planning method has been

realized. Therefore; in this thesis, the characteristics of EPS and the effects of them on different planning phases is handled. But before, to conduct a complete study, the main deficiencies of up to date production system paradigms and future production system characteristics are highlighted. Evolvable Production Systems (EPS) is presented and compared with the available ones. At the end; a proposed planning reference architecture for a fully reconfigurable system as EPS is introduced.

### **1.3 Research Approach**

The approach of this work is composed of 5 steps which are [3],

1. Primary investigation; literature review, gap analysis,
2. Problem and requirement identification; definition of requirements and problems which needs to be satisfied,
3. Conceptual and detailed design; conceptual development of the new approach or model,
4. Implementation; application of design/model on a test case or prototype,
5. Evaluation; assessing the performance of the model on the test case.

Implementation of a planning model requires software solution to be tested. Therefore implementation is aimed to be conducted at a test case environment. This research approach covers the whole PhD study. The work explained in this thesis embraces first 2 steps and also conceptual design of the proposed method.

### **1.4 This Work**

The structure of the thesis is composed of 3 main sections, where chapter 2 gives the literature survey, current planning methods and deficiencies of manufacturing planning control, following this chapter 3 highlight Evolvable Production System architecture and working principles and finally chapter 4 establishes the relation between these 2 chapters by highlighting the advantages enabled by EPS and also introduces a proposed planning reference architecture called Demand Responsive Planning (Figure 1-2).

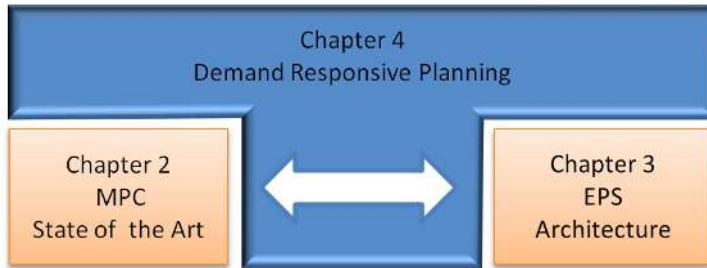


Figure 1-2 Thesis structure

## 1.5 Limitations

The proposed planning reference architecture has the coherent flow of planning activities where the main target is to achieve complementary model of production system and planning framework. However; in the scope of this thesis, the specific methodologies which can be embedded at different phases of the reference model are not detailed. They are highlighted at specific locations where they need to be implemented. Although the literature survey has been conducted for them it is not covered in this thesis nor the best fitting specific methods.

The framework of the preliminary planning reference model is kept limited only from the company perspective. Methods covering collaborative approaches with the suppliers that incorporate supply chain issues, sales planning and vendor management etc. are out of the scope of this thesis.





## 2 MANUFACTURING PLANNING AND CONTROL

### 2.1 MPC Framework

Manufacturing planning and control (MPC) deals with the systems and methods which coordinates all necessary mechanisms until the end user receives the demanded product. That is to say, it includes managing flow of materials, utilization of resources such as workforce and machines, coordinating suppliers and customers and so on. Different from historical perception of manufacturing planning and control, today MPC systems has to be dynamic and should overrule in a wide range of action. They have to be dynamic because the environments where the production systems are running are not stable. To be able to in line with the requirements of production system which can emerge from unexpected breakdowns, technological shifts and so forth, MPC system has to show dynamic behaviors, being in coordination with the other stakeholders who are a part of the system. MPC systems have to also overrule in a wide range of action because; if the planning system is aimed to be effective it has to reflect on the needs of the whole supply chain. The development of an effective manufacturing planning and control is the key to the success for any company.

Management board has the key function among the stakeholders MPC is in relation with. Main company strategies are granted through management board to MPC system and followed also through the feedback and figures provided by it. MPC can be considered as a tool for management to apply their strategies and conduct their production and supply chain activities. Besides, it serves as a decision support system for board.

Customers at one side have demands from MPC systems which can impose many irregularities such as complex and off the chart product types, urgent deliveries, canceled orders etc. On the other side, suppliers have their own limitations and rules which can contradict with the companies' perspectives. These can be quality problems on delivered components which can arise from varying reasons, delayed deliveries, packaging differences and so forth. MPC systems are in the middle of these 2 main stakeholders of the supply chain with the target of satisfying every

single customer through converting the components and raw material into desired end products. And at the same time the irregularities and unplanned events have to be handled in cost effective way without losing the track of company strategies. Hence, there are 3 main actors to which MPC system is in direct relation (Figure 2-1).

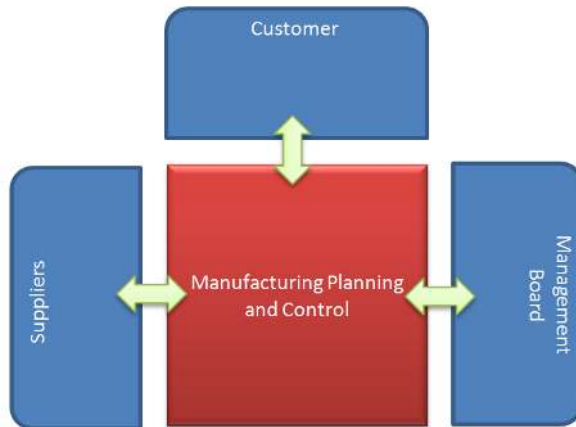


Figure 2-1 Actors in relation to MPC system

## 2.2 MPC in Supply Chain

In a wider view, a firm is a part of a whole supply chain which consists of several legally separated firms. Supply chain is defined as “ network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer”[4].

There are companies available which are putting different parts of a supply chain in nutshell. That is to say, it is common to combine manufacturing and assembly operations in the same plant. Organizations in the supply chain are linked to each other by flow of material, information and of course money. Today in most of the supply chains the information and material flow is fragmented between two successive organizations which causes varying problems and prevents to achieve effective supply chain strategies.

As in the arrows which represent flow of information in the above figure, information is transferred to the upstream actors in the supply chain from one to another. This restricts for the upstream companies to have knowledge of demand from the end-users. Without being informed about the consumption of end-users, the dependence to forecasts for upstream companies is substantially increasing. The reason is that demanded quantities are increasing significantly when passing through actors in the supply chain due to the intention of keeping safety stocks and decreasing backlogs.

Figure 2-2 reflects the overall relation between MPC systems and the actors in the supply chain in a more detailed way.

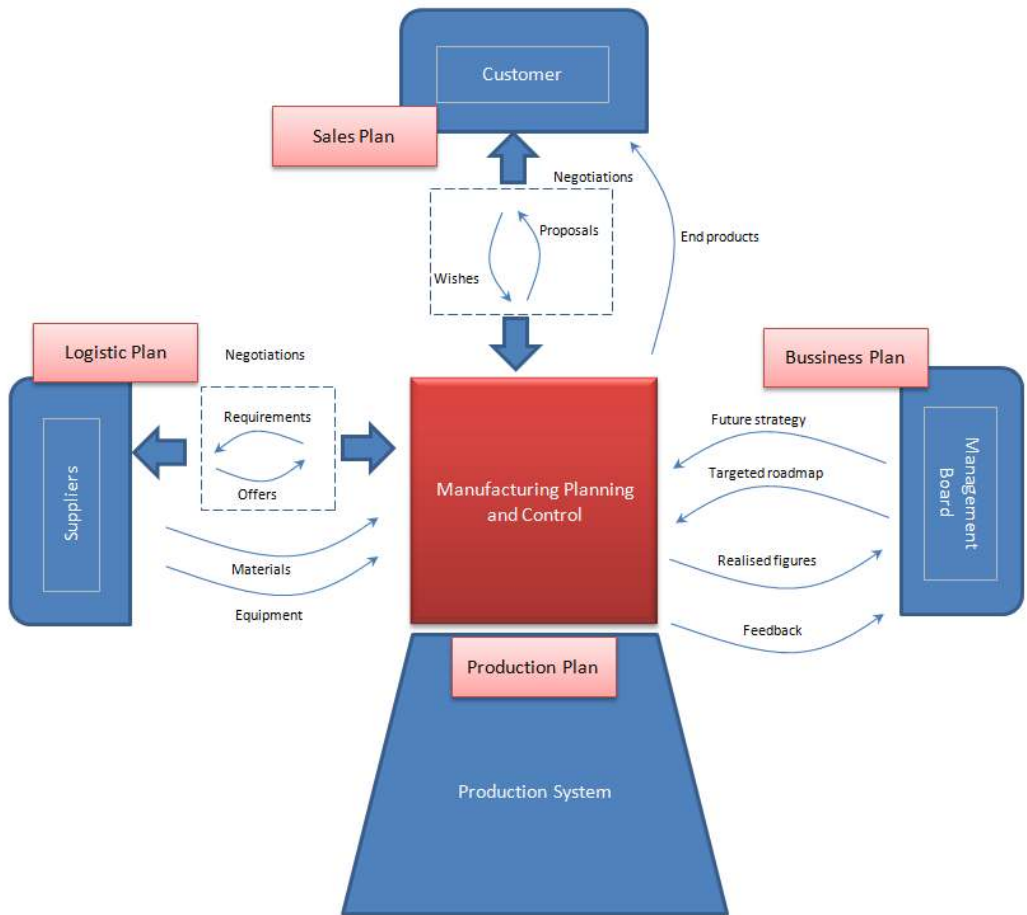


Figure 2-2 MPC Framework

*MPC and Management board,*

As mentioned previously, MPC systems are not decision giving mechanisms their selves at a strategic level however they directly affect on the decisions through supporting the management board with the available performance indicators. Management board is supposed to organize the business plan which includes future business strategies such as targeted markets and products, new investments and future directions from economical and operational point of view. Having the strategic framework for the company in hand, the production system planning and

its supporting mechanisms are designed and performed according to the methods chosen by MPC system. Furthermore, the link between the management board and production system is constituted by MPC system through the feedbacks which is supplied to board and reflecting the current condition and performance of production. These performance criteria are effectiveness, efficiency of varying parameters and evaluation of customer satisfaction.

Effectiveness is described in a very short way as “doing the right thing”. It involves optimality in the fulfillment of multiple objectives with a possible prioritization within the objectives. It is a sign of strategic high level performance.

Efficiency on the other hand is defined as “doing the thing right”. This entails productive use of resources through the conversion of input into output with a minimum amount or quantity of waste or unnecessary effort.

Customer Satisfaction is defined as "the number of customers, or percentage of total customers, whose reported experience with a firm, its products, or its services (ratings) exceeds specified satisfaction goals." [5] In a competitive marketplace where businesses compete for customers, customer satisfaction is seen as a key differentiator and increasingly has become a key element of business strategy [6].

### *MPC and Suppliers*

Suppliers in this figure represent, the firms who are providing;

- Raw materials to be processed
- Semi processed components
- Equipments

Although these classes can be detailed further, these 3 generalize the kind of flow from suppliers to the MPC system. Considering the high amount of material flow from suppliers to MPC system, and information flow from MPC to suppliers, supplier systems need to be structured in order to harmonize the flow between the firms. Such systems are called Supplier Relationship Management systems (SRM). The main functionality of these systems is setting up mutually beneficial relations with the suppliers who are bringing competitive advantage. The information flow to

suppliers is in the form of purchase orders. It is important to keep the purchase orders updated in the case of change in the priorities of the orders. This purchase orders are created by set systems which are integrated into ERP systems.

### *MPC and customers*

The relation between these two is actually where all the effort turns into the economical benefit and where the link is created to market which can be composed of the end-users, distributors, and other producers. Demand, as one of the essential factor in the dynamics of planning, incorporates uncertainties in itself which needs to be handled carefully in order to keep customer satisfaction level as high as possible. The relation between the demand and MPC systems are studied under the field of demand management which is one of the MPC system activities and will be clarified in this thesis.

### *MPC and Production System*

At the base of the Figure 2-2 production system block lies, which represents the phase where all the value adding activities are taking place by converting inputs through utilizing a range of resources into desired outputs. To generate effective outcomes from planning activities in a supply chain, that is to say stabilizing demand and supply balance in an economic way, requires having agile production system where the dynamicity of the market can be handled by both the agility of production and planning system. In the MPC systems today, production system and its constituents are considered as a black box that acquires input and extracts output. In fact, the processes inside this box, its requirements and essentials are one of the main determinant factors for the planning of a production system.

## **2.3 Manufacturing System Typology**

Planning activities show differences according to the characteristics of the manufacturing system. They can be classified in 2 ways according to their process flow structure and market relation which is defined with its customer order decoupling point location. It is possible to have different formations simultaneously

in line with the changing characteristics of the product. Classification according to process flow structure is as follows.

### **2.3.1 Process flow structures**

#### *Project work*

Project works are appropriate in order to produce unique products at a fixed location through moving resources as needed and coordinating them using project management techniques. Project work is characterized by the fact that all necessary equipment is moved to products manufacturing site unlike to manufacturing lines where process are located and products are flowing. Technically speaking, there is no flow of processes in this kind of manufacturing environment. From the product point of view, the variety of products that can be produced is very high whereas the product volumes are very limited due to standardization of the processes are not possible with changing product requirements for each single product. Human contribution in a project work is extremely high while the investment for capital is low.

#### *Job shop*

In a job shop environment general purpose machinery and equipment are utilized and there are a flow of products unlike a project work. Layout of the system is arranged in relation to process where the products are processed by following different routes in consistent with the workflow they have. Advantage is the capability of producing a high variety of products however efficiency is quite low. The equipments benefited in this kind of systems are general purpose and reliant very much on the knowledge of the workers.

#### *Batch process*

Batch process structure has higher standardization in processes in accordance with the product types in comparison to job shop process flow structure, at the same time, decreased capability of producing high variety of products.

### Assembly line

This kind of structure can be named as *dedicated flow line*. Assembly line connects the activities and paces them which provide high production rates for limited product varieties. The essential prerequisite to set up such a flow line is necessity to produce sufficiently large volume and at the same time low variety of products.

### Continuous flow

Finally, continuous flow has a fixed sequence and fixed pace where the flow of products is continuous.

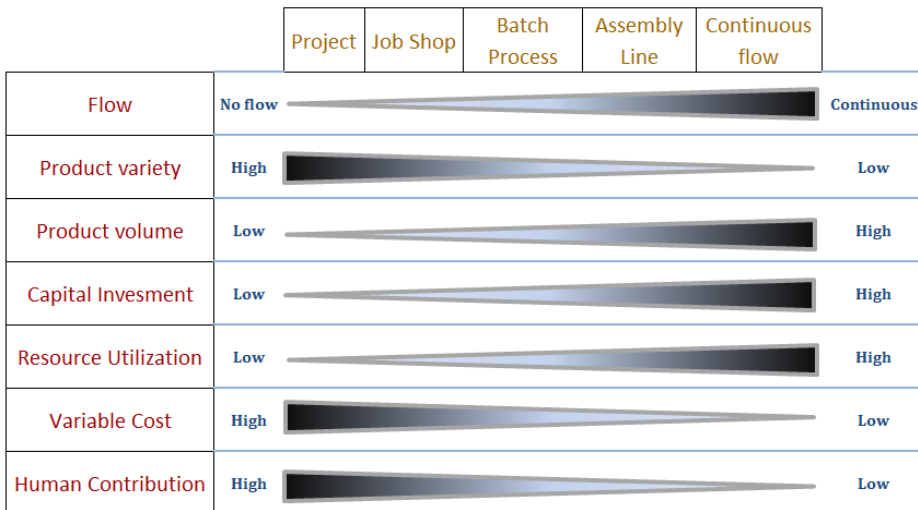


Figure 2-3 Process Flow Structures & Characteristics

Different process flow structures and their comparison according to different criteria are shown at Figure 2-3.

### 2.3.2 Customer Order Decoupling Point

Customer order decoupling point represents the strategic point in the value chain of a product where the product is linked to customer order to be pulled. In the literature sometimes, this point is named as Order Penetration Point [7, 8].



Different manufacturing systems are structured by establishing CODP at different positions which are clarified below.

### *Make to stock (MTS)*

At a MTS environment, products are stored at finished goods inventory after passing through all the necessary processes. The volume and timing of production of the products are assigned from planning systems which is dependent on the forecasts. This is a typical system for many industries like white goods, electronic products, food etc.

### *Assemble to order (ATO)*

Decoupling point for assemble to order systems are located between manufacturing operations and assembly. This means, products have required materials and components to be assembled in the case of a customer order arrives. ATO is prevalent for products having a large number of variants and long times for preparation of components. Comparing to a MTS system, this brings advantage on avoiding costly finished goods inventories.

### *Make to order (MTO)*

Producing and assembling in response to customer orders as in MTO systems denotes the decoupling point is located before manufacturing. MTO systems are feasible if the product is costly to keep in inventory and has a high number of variants, small quantity of demands. For MTO systems it is common that process planning is performed beforehand and customers decide the specialized product from the catalogue. Car producers can be an example for such a situation where the customer decides the parameters (color, 3 or 5 door, engine options etc.) and extras (navigation, sunroof and such). Since it includes customized parts it requires manufacturing process to be conducted after order is received.

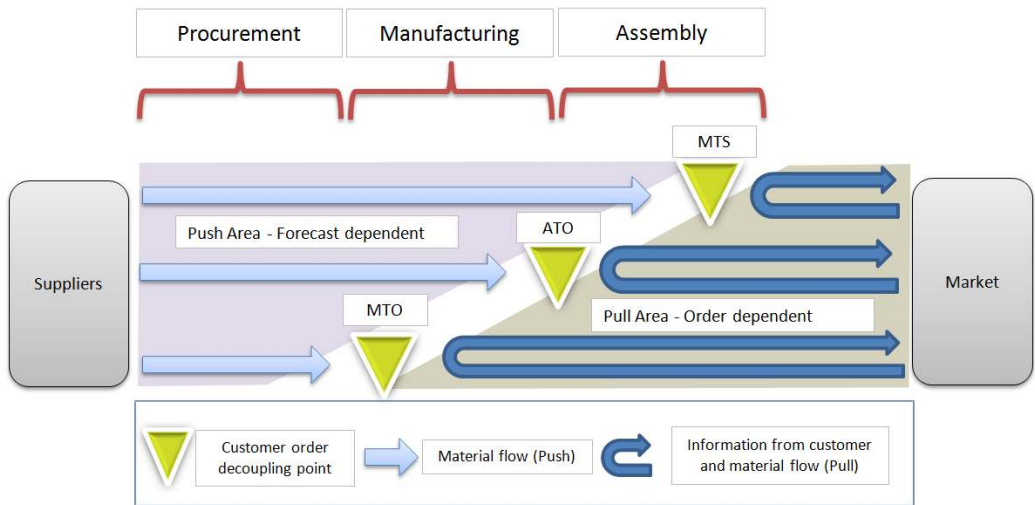


Figure 2-4 Customer order decoupling point

## 2.4 MPC System Activities

Activities in manufacturing planning are classified into 3 classes according to the effect that have over time. That is to say, the planning activities are aiming different time horizons such as long term, medium term and short term. As the time horizon narrows down from long term to short term, planning is done in a more detailed way from aggregate plan to very detailed shop floor plan.

### 2.4.1 Long Term Planning

In the long term, planning is conducted with aggregated figures in order to meet the demand in the market which is at different types like promised orders, forecasted figures and so on. The main objective in long term planning is to have a system which has sufficient capacity to provide the best balance between the supply and demand according to the company objectives. Capacity here refers to human workforce, machinery and equipment, the required material handling systems etc.

As far as supply chain relations are concerned, long term planning is supposed to take in to account that suppliers might not always enough competence and capacity

to deliver desired materials. That's why it is important to inform suppliers about the long term expectations beforehand to prevent future problems about deliveries.

There is no detailed shop floor activities encapsulated in the long term planning whereas the major decisions about future company strategies, aimed markets and products, sales policies are given. Master production scheduling activity in this phase has a critical function which will be detailed in this chapter.



Figure 2-5 Long term activities

### *Demand Management*

Demand management block is the one which is establishing market connections and with this link provides inputs to MPC system. These inputs are in 2 types, independent demand and dependent demand. Basically, the independent demand represents the customer orders which are not possible to be known beforehand and independent from company. Whereas, dependent demand is reliant on the orders taken and represented in the form of material or equipment. Calculating dependent demands is a straightforward process with the aid of required information about the ordered product. Having bill of material in the hand for each product types, material and component requirements for products are easy to calculate. For independent demand types, it is not that simple. The real challenge is estimating the long term future demands to be able to support the capacity planning and investment decisions. Estimation of future demand information is fundamental for the current MPC systems to be able to set up the production system accordingly. From economical point of view the best scenario happens only if you know forthcoming orders beforehand and unfortunately this is not possible without knowing the future. Forecasting methods are developed and used

commonly in long term planning activities in order to find the best approach to approximate future demand information.

### *Sales and Operation Planning*

Sales and operation planning activity is the key communication link for top management to coordinate the various planning activities [9]. Top management plans are integrated to MPC system by this block in the form of marketing planning, strategic planning and financial planning. In this activity the main function is providing a framework for master production schedule to be able to balance demand and supply at aggregated figures. What is more, the overall production information for product families is also assigned from this block to MPS. Decision on aggregated production volume of different product families is mostly dependent on past data and forecast methods. That is to say, this block is the one which is trying to find the best fit between the reality and estimates through evaluating tradeoff between various factors in order to meet company objectives. Sales and operation planning is not specifically handled in this thesis but given for the purpose of reflecting a comprehensive picture of today's MPC systems.

### *Resource planning*

Resource planning in this level is conducting aggregated capacity planning decisions. The function of this activity is to convert long term data from sales planning into aggregate resources like labor hours, floor space, machinery, warehouse space etc.

### *Master Production Scheduling (MPS)*

MPS takes information from sales and operation planning as input which is translated into output that includes a production plan for specific products for the future. That is to say, the aggregated information is converted into a more detailed plan where the production quantity and timing of particular product types are apparent.

The essential feature of this activity is being the phase where the unpredictable and stochastic environment turns into deterministic (forecasted) environment and accepted after this step as it is. Although in most of the case MPS has a dynamic

structure by being updated with new information, it is fed by future estimates and works efficiently as long as the forecasts are consistent with reality.

MPS basically is the conclusion of long term planning activities and transferred as input to intermediate term planning as starting point for material planning and capacity planning. It takes into account customer orders, forecasts of future demand, safety stock requirements, seasonal plans and internal orders from other parts of the organization.

#### **2.4.2 Intermediate Term Planning**

Intermediate term, on the other hand, is the phase where aggregated figures coming from long term plan are disaggregated to be able to have a match between the equipments and planned production for each certain time period. The focus here is on providing exact material and production capacity needed in order to meet the requirements coming from master production schedule. That is to say, aim is to provide the right quantities of material to arrive at the right time and place. One other task which is conducted in this phase is providing expected order delivery information and also coordination with suppliers in order to receive deliveries accordingly.

It is important to emphasize the way of relation between long term planning and intermediate term planning in order to specify the ambiguous circumstances arising. Since in the long term planning, aggregate quantities and measures are taken into consideration as a first step of overall MPC, the target of detailed planning between supply and demand will rarely fit to the requirements which are imposed by MPS. The reasons will be clarified later in the thesis. However, results of this issue bring to medium term activities the responsibility of making capacity and material adjustments in order to meet the demand. These adjustments are conducted in terms of planning overtime works, subcontracting materials, obtaining equipment etc. All these are actually bringing extra burden, causing instability and filling the gap which occurs through disaggregation of aggregated plan.

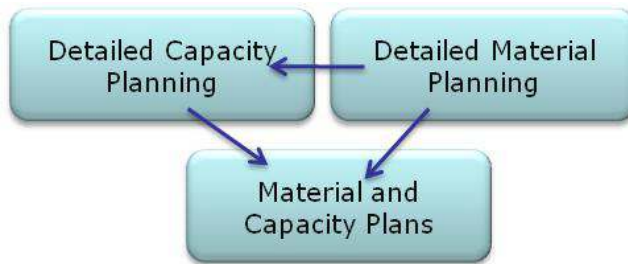


Figure 2-6 Intermediate term planning

### *Material Requirement Planning (MRP)*

MRP is one of the most common methods to determine the production quantity for every period and time for material ordering for end items. MRP and Just in time (JIT) is handled at next section with a comparison to each other.

### **2.4.3 Short Term Planning**

In short term planning activities, day by day plan of resources are prepared according to the input coming from upper level activities. This entails arrangement of material, equipment, people, time, facilities and so forth. This level planning influences shop floor level systems. Essential issue here is the precise planning of work distribution over resources in order to attain the best figures concerning the performance indicators. Shop floor level systems and supplier systems construct short term level activities.

Today's MPC systems are equipped with control mechanisms to be able to monitor the execution of plans and react in case of unexpected problems at shop floor level. Control mechanisms are essential for a MPC system and they consist of measurement, follow-up and control of actual results. For the shop floor activities the consistency of the real production and planned one is monitored. There can be deviations from the planned product quantities, rate of production and timing of specific completions. Control mechanisms at available solutions for the companies in the present day, like ERP, are functioning at shop floor level and supplying feedback to shop floor level planning activities in order to take action.



Figure 2-7 MPC System Activities

As in Figure 2-7, a general MPC system is composed of several planning activities which are classified according to time intervals. Although the encapsulated functionality for a MPC system is same as a whole for companies, the flow and the distribution of activities might show differences according to the companies for some reasons. These are principally;

- Production processes
- The degree of supply chain integration
- Customer's expectations
- The needs of management.

## 2.5 Push & Pull Production Philosophies

There are 2 main philosophies for moving material through the system which are Push and Pull philosophies. In a *push system* the material forward to next station according to a plan without concerning the state of the next station. However, in a

*pull system* items are moved between two successive stations only when requested from downstream station.

### 2.5.1 Material Requirement Planning

Characteristically, Material Requirement Planning (MRP) is a push system because the basic structure has a hierarchy starting from the top level long term planning and branches out until the lowest level (Figure 2-8). MRP starts with collecting information for each end item to supply data for the preparation of MPS over the planned time period which is generally long. These data are collated into MPS and used as an input to MRP. According to the outcome of the MRP system the shop floor schedule and raw material supplies are coordinated.

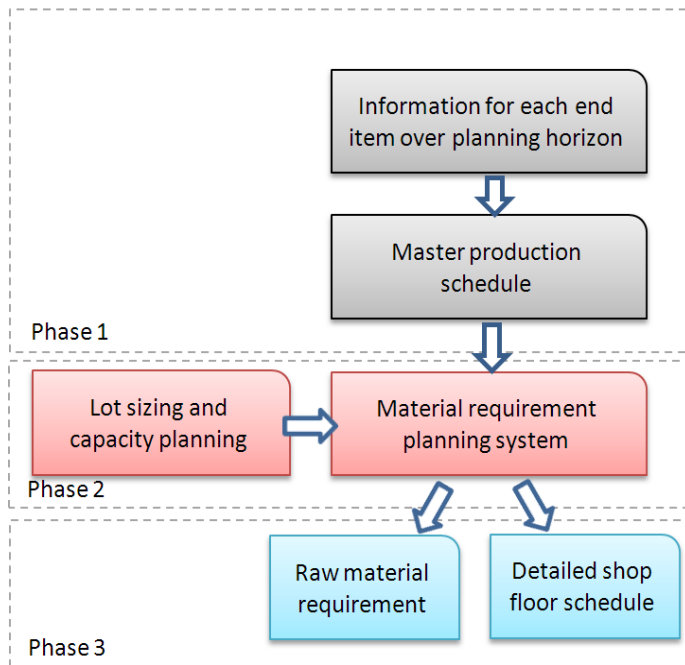


Figure 2-8 MRP Hierarchy

The flow information for a MRP structure as a block box is shown in Figure 2-9. Inputs which are required for a MRP are on hand inventory, bill of material where



the part type of quantity for each product is specified, scheduled receipts which are promised orders by the customers, and MPS.

MPS is organized at strategic level planning where the production roadmap of the company is derived including seasonal plans, dependent and independent demand information, safety stocks and so on.

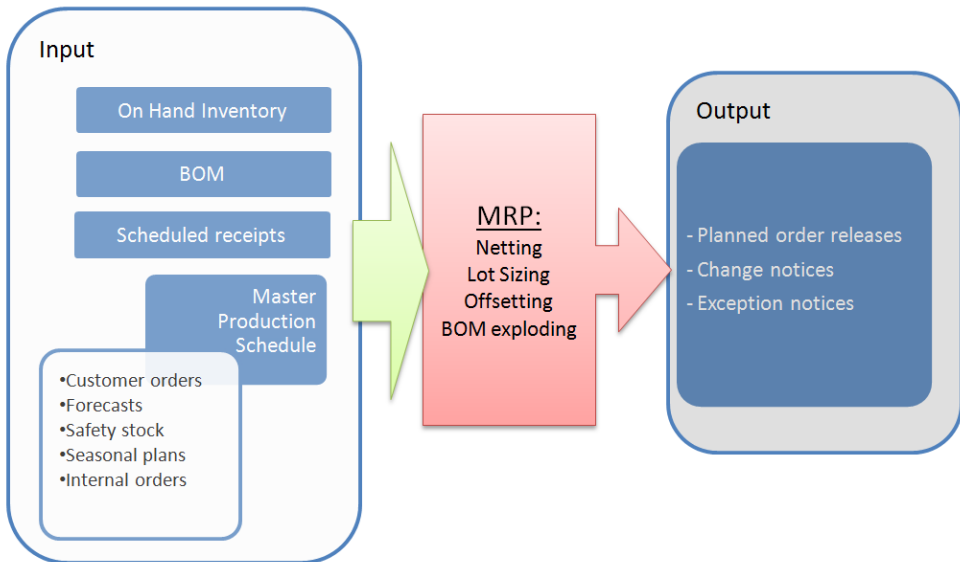


Figure 2-9 MRP as a Black Box

The generic stages that a MRP system follows are netting, lot sizing, offsetting and BOM exploding. Since the stochastic part of the planning is handled inside MPS through different forecasting methods, MRP steps are straightforward. To clarify shortly;

Net requirement for a specified period  $t$  is calculated by subtracting the previous periods on hand inventory and scheduled receipts from gross requirement. Gross requirement is the amount which is transferred to MRP from MPS.

For a specific period  $t$ ,

$$(\text{Net requirement})_t = (\text{Gross requirement})_t - (\text{On hand inventory})_{t-1} - (\text{Scheduled receipt})_t$$

Having net requirements in hand, to be able to calculate the time adjusted net requirement, lead time for that specific product is necessary. Lead time represents the time between the order arrival and order completion.

$$(\text{Time adjusted net requirement})_t = (\text{Net requirement})_{t + \text{lead time}}$$

Finally, planned order release takes into the account the lot sizing algorithm that the company is using in order to determine the time and the quantity for ordering which has relevant lot sizes. A planned order release is the end result of a MRP system.

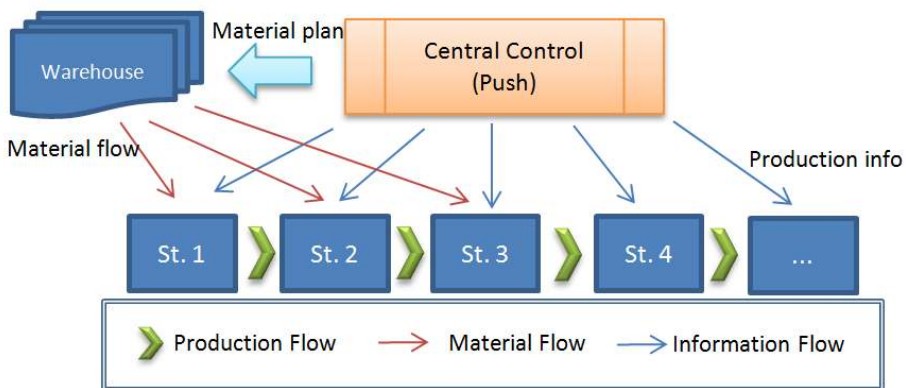


Figure 2-10 Information and Material flow of Push Philosophy

### 2.5.2 Just in time

In a pull system, the material flow starts with the introduction of a demand. The main difference between push and pull system is the trigger of production. In push systems start time and quantity of production is determined beforehand and the system targets to follow this schedule whereas in pull systems; production starts with the information coming from the downstream station or machine which is in need of material. Just in time (JIT) has been introduced by Toyota as a characteristic application of a pull system. JIT is described as the basis of Toyota production

system where the right parts are needed in assembly line at the time they are needed and only in the amount needed [10]. It is important to emphasize that JIT reflects a management strategy rather than a physical system [11]. This philosophy necessitates new requirements from the operational and production system point of view.

Before clarifying the working principles of JIT, it is fundamental to analyze the enablers of the transformation from a settled MRP system to just in time. Toyota has developed a method which is called Single Minute Exchange of Dies (SMED) whose main purpose is reduction of changeover time between products who has different process requirements. The pursued method is separating the setup time into two parts which are internal and external setup. External setup includes the setup operations which are possible to be conducted throughout the production system runtime whereas internal setup operations require the production system to cease. Hence, the more the setup operations are transformed into external setup, the shorter the production system stops during changeover. This critical improvement in the shop floor, namely reduction of setup time, created opportunities to the planning system by means of enabling to decrease lot sizes so work in process inventories.

Another cornerstone for JIT was introduction of Kanban cards which are used for both triggering production for upstream stations in the line and ordering material if the critical level is reached. Outstanding contribution of JIT to production management was enabling to keep the control of work in progress (WIP) on the shop floor through proper flow of information by kanban cards Figure 2-11. shows a sample pull system where the flow of material, production and information are conducted by kanban cards. Production at different stations are only initiated by the arrival of production kanban and the material flow by material kanban.

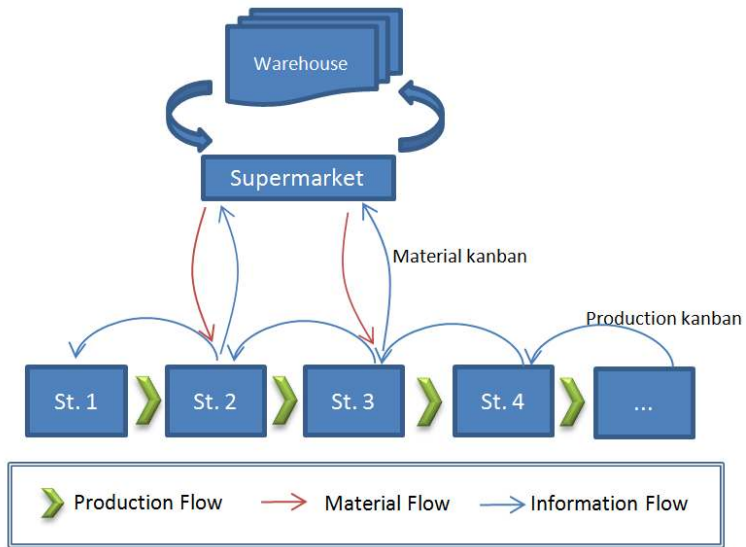


Figure 2-11 Information and Material flow of Pull Philosophy

Improvement provided by JIT concept is limited to shop floor level. Planning model of a pull system (Figure 2-12) follows hierarchic sets of decisions where the capacity and material planning decisions are dependent on long term forecasts [12].

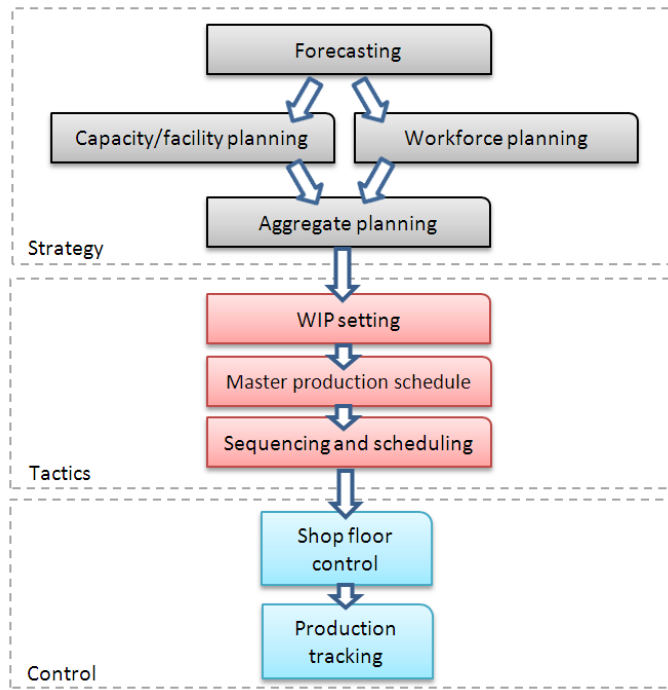


Figure 2-12 Pull Planning System

## 2.6 Problems with MPC systems

Current MPC systems do not properly cover the planning and control problems arising in the industry today. Many planning systems are able to function in an effective way if the conditions and assumptions are met. What is more, conditions and underlying mechanisms might not be recognized and applied before implementing the solution. In such a case it is highly probable that results in unexpected and ineffective outcomes. To exemplify these assumptions, highly reliable manufacturing system, known product structure, faultless future information, fixed lead times, no capacity limitations, a limited number of product varieties etc. And even, planning methodologies which are purchased as a software package are influencing the production practices just to conform the prerequisites of the planning methodology.

Available planning mechanisms, regardless of operating according to push or pull mechanisms, rely on the aggregate plans whose content consists of long term estimates of many parameters. Disaggregation of the data until reaching a certain plan where the job allocation to resources is fixed, capacity decisions are determined, time to order for material and time to start for production are set, accommodates substantial risks. It is not uncommon to calibrate the plan along with the new situations arising in order to attain targets. Occasionally the actions taken are in the form of modifying the workforce, adding overtime work, delaying order delivery with a cost of a kind of compensation, increasing capacity if possible etc. Those, who cannot patch the plan, end up increased backlogs, decreased quality of products and all these bring about power loss in the competition.

Problems throughout the application of MRP systems come to the fore, first of all, as capacity infeasibility, since capacity is not considered as a limitation in MRP systems. This problem has initiated studies which resulted in MRP II. MRP II has offered solutions in order to take actions before capacity problem is met in the shop floor through revising master production schedule prior to applying it [13]. Enterprise Resource Planning (ERP) solutions include MRP II and established relations to other business functions like financial accounting, manpower planning and so on; however, it did not add any function towards intelligent planning [14]. As far as the relation of production system characteristic and planning system is concerned, the real problem actually is the inability of rapid shrinking or extending the capacity of production system along with changing needs. If the production system would allow integrating new processes for an unforeseen product requirement and/or increase the capacity in response to unforeseen volume fluctuations, major capacity related problems became redundant.

Secondly, fixed lead times are used at the offsetting step in MRP, which is in fact varying depending on the disturbances in the production system. To overcome this issue, either more safety stocks are kept on the shop floor or lead time is increased by some percentage. Increase of lead time results in early production of the orders which in turn causes high finished goods inventory. Both of the situations result in higher inventory levels which results in lack of responsiveness and higher inventory costs. As another problem of MRP, system nervousness which is explained as big

effect on the low level shop floor schedule of a small revision in MPS. Revision in MPS might be required in some cases like updating forecasts, failure of equipment, problems with the suppliers, personnel problem etc. However in some cases the revision of MPS might result in inefficiencies at shop floor on time and quantities when changing the production plan from one MPS to another.

Just in time, on the other hand, has vital prerequisites to be provided in order to work properly. On a shop floor where high number of product varieties is aimed to be produced, JIT would fail due to increased buffer between workstations. Furthermore, since the WIP level is low at a typical JIT production a machine breakdown at a point in the line causes to stop whole line. This situation needs to be solved by planned concerning the tradeoff between the WIP level and effect of a single station stop to whole line. What is more, JIT production systems are not responsive to changing situations like product volume and variants. As far as logistic matters are concerned, JIT is highly dependent on the coordination with the suppliers because a delay in one of the critical components can affect whole system.





## 3 EVOLVABLE PRODUCTION SYSTEM

### 3.1 Background

The majority of the problems that planning systems are facing arise from the fact that production systems are not fully adaptable to fulfill the requirements which cannot be predicted beforehand. To be able to release the constraints which are imposed by production system and also to adapt to dynamic market conditions, *next generation production systems have to be more strongly time oriented*, i.e. highly responsive, while still focusing on quality and cost. According to Shen et.al. [15], the necessary requirements to achieve this are; (1) full integration of heterogeneous software and hardware systems within an enterprise or across a supply chain; (2) open system architecture to accommodate new sub-systems, both hardware and software, or to decompose existing sub-systems; (3) efficient and effective communication and cooperation within an enterprise or across enterprises; (4) embodiment of human factors; (5) quick response to unexpected internal or external disturbances; and (6) fault tolerance both at the system and sub-system level to diagnose and recover system failures. The attempts to attain responsive production systems have resulted in a number of production system paradigms.

Flexible production systems [16] targeted to encapsulate the required abilities and functions of one or a few similar product families in one unit. It is a costly solution since end users are obliged to purchase extra process capabilities even though they will not need. In case of new product requirements which are beyond the available capabilities are introduced, configuration of the system became costly and/or time consuming or even impossible. Furthermore flexible production systems were inadequate to meet the requirements with its centralized and hierarchical control system[17].

Modular production systems aim to overcome the challenges of the market by building flexible production systems from standardized modular machine elements. The module categories are composed of four classes, namely process machine primitives, motion units, modular fixturing and configurable control systems [18]. Once the manufacturing system reconfigurability is targeted, the control architecture has to be given priority since the reprogramming takes considerable fraction of reconfiguration. Unless the modular elements are combined with

distributed control systems, which can be realized by embedded computational power to the modules, the real reconfigurability cannot be reached.

Reconfigurable production systems went one step further and developed modular approach to the production equipment for the purpose of increasing reusability. This enabled the system to have flexible capacity and functionality together with reusability [19]. The key characteristics of a reconfigurable system are modularity, integrability, convertability, diagnosability and customization. The reasons why reconfigurable systems could not achieve true reconfigurability are; firstly, intelligent and distributed control systems were not benefited in the production environment, secondly reconfigurable systems were focusing only on production environment and did not evaluate the whole enterprise with product design, organization, operation etc. and finally modularity of the equipments could not enable short deployment time without supplying autonomous components.

Holonic manufacturing systems introduced the concept of holon which stands for any unit that encloses an information processing part and optionally a physical processing part. These units are classified as resource holons, product holons and order holons [20, 21]. There are 2 fundamental characteristics of a holon which are autonomy and cooperative behavior. The control structure of holonic systems lies between fully hierarchical and heterarchical structures to compensate a weak point of fully heterarchical control systems, which is the inability to guarantee a certain global behaviour and performance [22].

Comparing to the current paradigms the aim of EPS has not been to develop limited flexibility or barely physical reconfigurability with central control mechanisms [23]. The focus of EPS paradigm is to achieve overall system adaptability by modules which are dedicated to specific processes with the capability of short deployment time at shop floor without reprogramming effort. Modules are the basic building blocks with the characteristics of being process oriented and embracing embedded computational power in order to enable autonomous behaviour based on multi agent system architecture. In EPS approach intelligent modules form a dynamic network for the purpose of dealing with production system requirements by means of collaborative behaviour. Main characteristics which are envisaged by Evolvable Production System is clarified below.

### 3.2 Process Oriented Modularity

A module can be described as the smallest building block of a system. Possibility of assigning varying functionalities to modules, their aggregation capabilities and contribution to control system grounds modular structure to have a wide application area in industry. Issues arising with modular systems include: accomplishing granularity at lower levels (fine granularity) where modular characteristics are shown; developing interface of the modules in order to communicate both to internal and external environment; defining skills and capabilities assigned to modules; and advancing abilities of cooperation and creation of coalitions in order to achieve a common target and their methodologies. EPS modules are designed according to the process needs rather than a specific product family. Figure 3-1 represents a traditional way of building system where the product requirements are imposed to production system by leaving freedom to product designers and assigning complexity to production systems. Furthermore, most of the product specific equipments become obsolete after the product life comes to end. In the case of new product requirements are introduced to system, the available equipments are missing to be reused due to being product specific. However, the processes which are actually benefited can be repeated with new system design as in Figure 3-2.

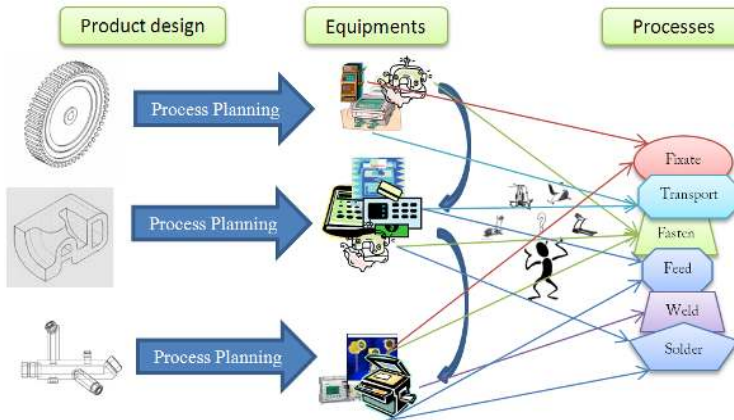


Figure 3-1 Traditional system design

Process oriented modularity is a fundamental cornerstone of EPS. Process-oriented modules feature skills that can be mapped into the processes and therefore in the product requirements. Each Task in a process can be exploded as a series of

operations that involve a variable number of basic activities. This means that a process needs a rather big set of skills to be performed. The equipment owns these basic skills and when different modules with the right skills are put together we have an EPS [24].

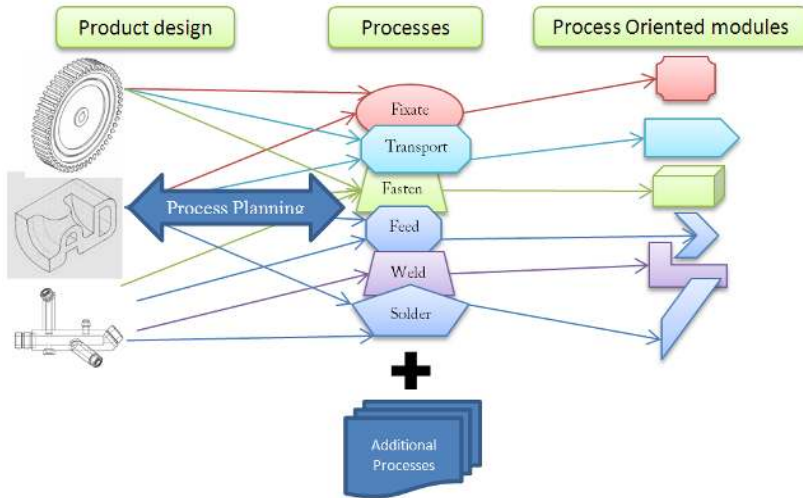


Figure 3-2 Process oriented system design

Skills are in 2 types in EPS such as Atomic skills and Complex skills [25]. The atomic skill is the skill for what the module has been designed. They are directly associated with the manufacturing components. “Move” is the Atomic Skill of a robot. The Complex Skills are on the other hand the skills that emerge when more manufacturing modules are put together and cooperate [24]. To exemplify, the complex skill of pick and place is composed of 2 atomic skills, namely the skill of grasp which is settled into a gripper module and the skill of move which is settled into a robot arm.

### 3.3 Multi-Agent Based Distributed Control

Manufacturing control accommodates managing and controlling physical and information processing activities in the factory aiming to execute production plan. In the case of a new system configuration is required, the challenge is not only achieving a rapid physical setup but also reconfiguring the control system. The evolution of control architectures has been analyzed by Dilts et al. (1991) under four classes: centralized, proper hierarchical, modified hierarchical and heterarchical [26]. In centralized control all systems activities and control decisions are managed

in a centre. Although centralized control has the advantage of obtaining global information in one place, enabling global optimization, it lacks the responsive ability to handle issues of expanding and shrinking assembly system due to complication of modification. On the other hand, distributed control system is characterized by autonomous components without different levels of authority to defeat the problems arising with hierarchical control. It is aimed to achieve full local autonomy, distributed decision making for activity coordination, no master/slave relationship and only local databases. Global decisions are made by cooperative approach of autonomous components. Improvements coming with distributed control are [27];

- Diminishing long-term instability due to shorter reaction delays.
- Re-initialisation and reconfiguration issues which arise due to disturbances or system shutdown are becoming less complicated to manage.
- Enhance product traceability and enable more active products throughout the entire lifecycle.
- Eliminating different levels of control authorities prevents reorganization and reprogramming of higher level control elements every time a component is added or removed. This characteristic allows the control system to adapt more easily in response to unexpected disturbances occurring in internal and external environment.
- Facilitate supply chain collaboration mechanisms, as well as collaboration in virtual and networked enterprises or companies.

According to Barata et.al 2001, the multi-agent systems represent a suitable technology to support the distributed manufacturing environment [28] since the manufacturing applications present characteristics like being modular, decentralised, changeable, ill-structured and complex, for what the agents are best suited.

Agent is defined as a computational system that is suited in a dynamic environment and is capable of exhibiting autonomous behavior [29]. Multiagent system is defined as a environment where the community of agents are interacting [29].

According to Monostori et.al (2006), the most important characteristics of computational agents are,

- Agents act on behalf of their designer or the user they represent in order to meet a particular **purpose**.

- Agents are **autonomous** in the sense that they control both their internal state and behavior in the environment.
- Agents exhibit some kind of **intelligence**, from applying fixed rules to reasoning, planning and learning capabilities.
- Agents **interact** with their environment, and in a community, with other agents.
- Agents are ideally **adaptive**, i.e., capable of tailoring their behavior to the changes of the environment without the intervention of their designer.

Analyzing the benefits of multi-agent technology it is possible to conclude that it fulfils some of main requirements of the actual distributed manufacturing systems: **autonomy** (an agent can operate without the direct intervention of external entities, and has some kind of control over their behavior), **cooperation** (agents interact with other agents in order to achieve a common goal), **reactivity** and **pro-activity** (agents perceive their environment and respond adaptively to changes that occur on it). Last, agents can be organized in a decentralized structure, and easily reorganized into different organizational structures [30].

The proposed multi agent system framework is composed of heterogeneous modules that execute different functions in the system. The architectural building blocks under the concept of mechatronic agent are shown below,

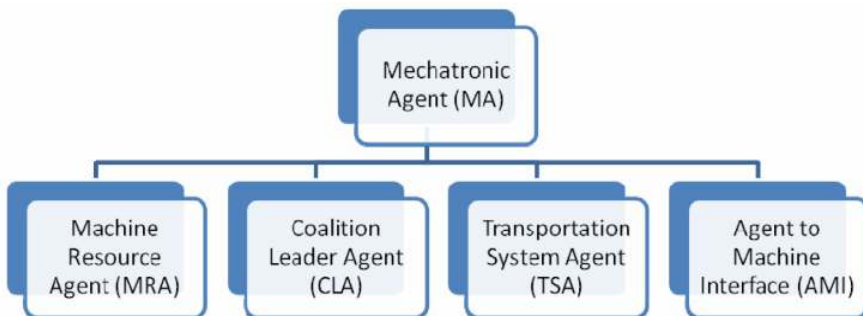


Figure 3-3 Architectural building blocks[31]

A mechatronic agent (MA) is composed of a controller and a physical part to conduct the function which it is designed for. The Machine Resource Agent's (MRA) main purpose is to abstract mechatronic modules that can be plugged and unplugged from the system and that host a set of executable skills. The Coalition

Leader Agent (CLA) is a construct that enables the composition and execution of skills. A CLA supports the execution logic of processes which are designed by the user based on the available skills in the system. The Transportation System Agent (TSA) abstracts components of the transportation system. It provides localization, transport and positioning functionalities. The Agent to Machine Interface (AMI) works as an harmonizing layer between dedicated hardware configurations and the MAs when the existing hardware does not support, from a computational point of view, the MA or the technical integration dramatically reduces the equipment's performance [31].

At the multi agent architecture which is developed for Evolvable Production Systems, the functional relations between mechatronic agents are conceptually defined in Figure 3-4.

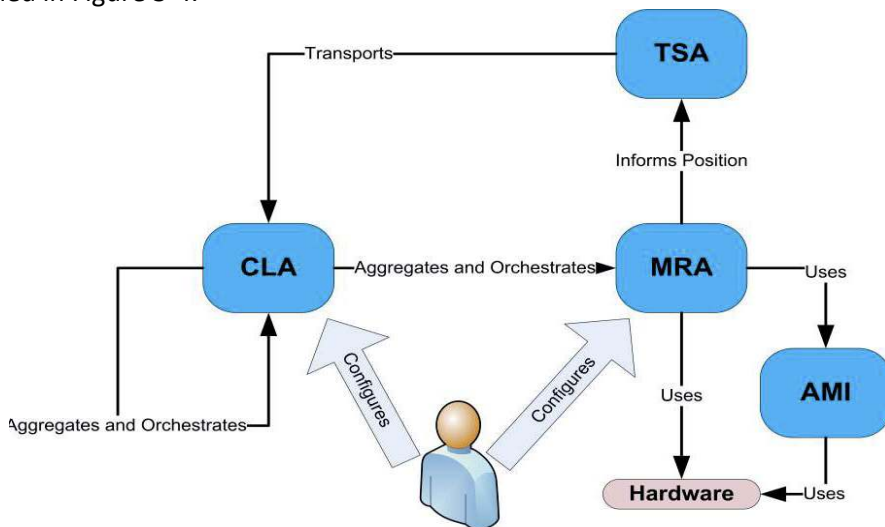


Figure 3-4 Functional relations [31]

### 3.4 Operational Working Principles

The architectural building blocks and their functionalities for EPS multi agent structure are described and to have a better picture the operational working principles of such a system needs to be clarified further. At the shop floor, the flow of product agent through the system is following the process sequence located in workflow file which is specific to different product types. Workflow basically includes the list of necessary processes and skills to achieve the end product. It

comprises also the dependencies between the required processes in order to give an option in the case of the resource which supplies the process in the queue is not idle. In this case, with the help of dependency information between the processes the product agent can ask for the other process from the available resources in the workflow as long as the busy process does not precede the next one.

The main advantage comes with the plug and play modularity where the requirement of reprogramming every time the system configuration changes is avoided. That is to say the time to set up the system in response to produce a new set of products is a matter of seconds as long as the required modules are available in the module repository. The implementation model for evolvable system[24] in the following figure clarifies the flow starting from the product requirement introduction until the design of the workstation to meet these requirements.

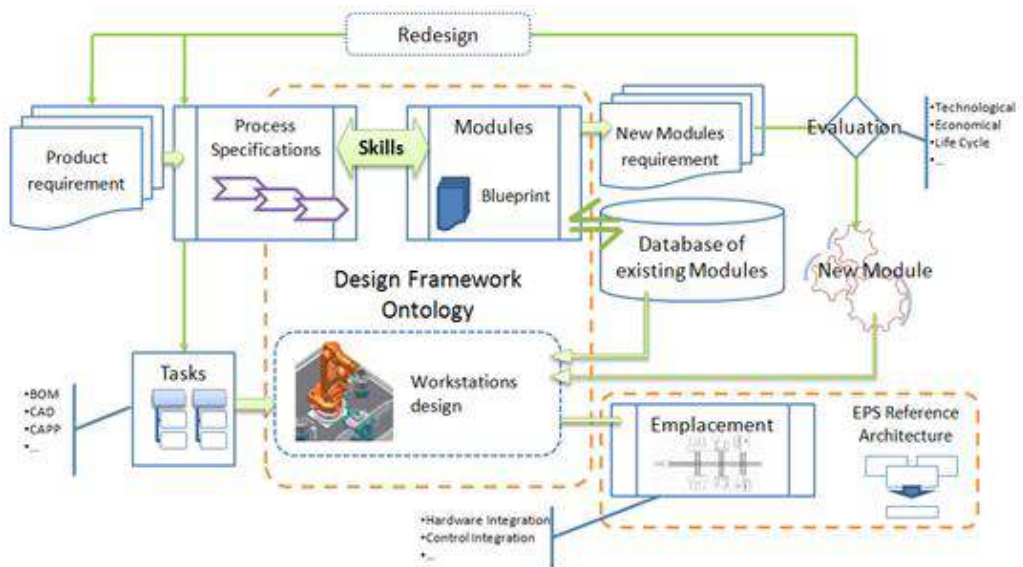


Figure 3-5 Implementation model for EPS[24]

For the modules to form a complete system, they are required to follow a structure which is called System Architecture in EPS. A System Architecture is an abstract description of a specific system. It depends on engineering principles and available technology; its main purpose is to specify:



- Functions of the system component
- Interaction
- Dependencies
- Interfaces
- Constraints

This abstraction helps in developing and re-developing the system along with improving the communication in the chosen domain[24]. System architecture is an instantiation of Evolvable Systems' Reference Architecture. The reference architecture (RA) describes the essential features of an evolvable system which means the RA specifies the necessary features that a system should have to be an evolvable system [32]. Main technical function of RA is to set evolvable system design and implementation decisions and objectives at a technical/technological level that describes the ontology, exploited protocols, standards or specifications for use with each major architectural component. As another major function RA includes reusable diagrams, graphs, objectives and knowledge and rules that address the distribution of system functions and how they relate topologically. Templates use models to show relationships and between components as specified by the technical positions and pertinent knowledge units[32].



## 4 DEMAND RESPONSIVE PLANNING

This chapter is addressing 2 subjects in order to merge chapter 2, elucidating overview of the manufacturing planning and control systems at different planning levels and chapter 3, detailing the architectural and working principles of evolvable production systems,

- First, the impacts of the operational benefits ensured by evolvable production system on different levels of planning activities are analyzed.
- Second, in the light of this analysis, a comprehensive planning reference architecture called “**Demand Responsive Planning**” is introduced which is a preliminary model, being compatible to fully reconfigurable systems as EPS and overcoming major deficiencies led by planning systems.

Before going into deep with these subjects, it is important to position Evolvable Systems considering its operational characteristics in manufacturing system typology by 2 means, as process flow structure and customer order decoupling point position. Manufacturing system typology is explained at Chapter 2.3.

To start with the process flow structure, the characteristics and architecture of EPS does not fit any of the available class properties whereas it can be mapped in fact as a combination of different features of available classes. Figure 4-1 represents EPS position in comparison to other process structures in light of varying criteria. Red markers on the figure represent where EPS is located for those specified criteria. Each of them is pointing a direction which corresponds to enhancement direction of the system in response to evolution of it which brings not only structural benefits but also operational continuous enhancements.

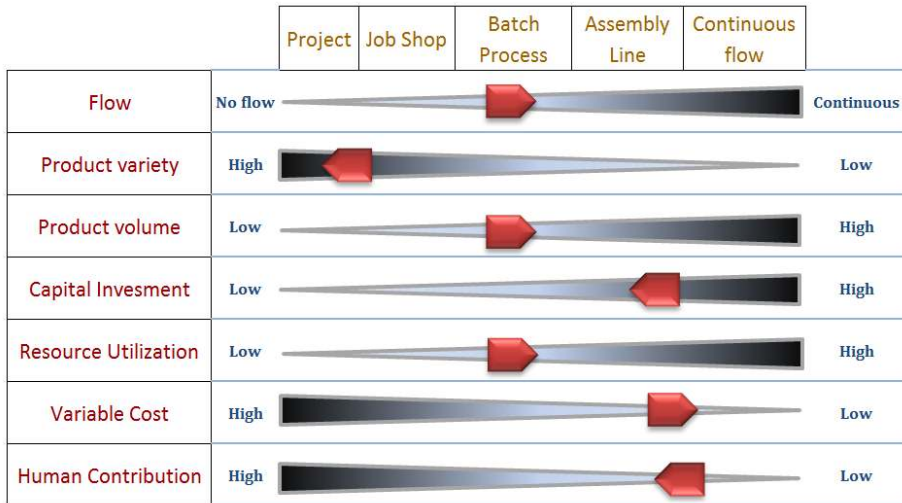


Figure 4-1 EPS position

Bearing in mind, at the shop floor multi agent architecture is benefited where each product agent has its own workflow and follows it according to the availability of the resources after several message exchanges, the volume and flow of the product passing through the system per unit time cannot be as high as an assembly system which is dedicated to a limited number of product varieties. As far as the product variety is concerned, it is one of the most important factors bringing competitive advantage to evolvable systems. Since system reconfiguration can be conducted according to the product needs through adding or removing modules in a very short time without the necessity of reprogramming effort, the number of product variety which can be handled with evolvable system can be so high as long as they are in the same domain. That is to say, you cannot change the system from assembling cell phones to watches however it might be possible to change from iphone to ipad if the proper modules are integrated to the system. That is why EPS might not be economically advantageous like a project work shop floor if you want every single product to be unique however it can produce as good results as a job shop process structure in view of the range of products.

Although there is no cost analysis conducted, from the capital investment point of view, intelligent modules with embedded processor will bring extra cost. However it

will provide superior return on investment figures as an outcome of the reusability of the modules in the long term since the modules are designed according to process characteristics which can be benefited for varying product requirements.

Resource utilization on the other hand cannot be as high as an assembly system considering the shop floor working and scheduling principles of multi agent system of EPS modules. For certain situations, resource utilization, as performance criteria, can be a misleading factor by causing costly consequences such as high end product inventory, increased waste etc. That is to say, increasing resource utilization might not be a correct target to increase profitability. In order to compare EPS, looking only at the resource utilization for a certain time interval would bring confusing consequences since the factual benefits arise with a long term approach with a holistic view instead of only focusing on resource utilization.

Variable cost in the figure, stand for unit cost of the product. The cost analysis is conducted on 2 parameters called fixed and variable costs. Fixed costs are not related to product sales volume whereas variable cost is dependent directly on the number of products sold. At Figure 4-1 fixed cost has not been used as a criterion to avoid misleading comparison, since it encapsulate cost items which are changing to a large extent from industry to industry such as rental costs. As a replacement capital investment, one of the items of fixed cost, is used and it reflects the equipment cost.

It is complicated to have a rough numeral for variable unit cost of EPS in comparison to other structures. 2 main constituents of variable cost are; the cost of raw material and cost of labor, both are increasing with increasing rate of production in conventional systems. However, EPS, having autonomous shop floor control through intelligent modules, does not require increasing human workforce with increasing production. Growing demand is satisfied through increased investment to modules which is classified as fixed cost. Hence, variable cost becomes dependent mainly on raw material cost for EPS which can be considered similar as highly automated assembly systems.

Human contribution should be handled at different levels of the whole system. For the Figure 4-1, it corresponds to human effort on production at shop floor level. In

the current architecture of EPS, human effort is benefited at the reconfiguration of the system in order to set the system physically up. Control system is autonomously configured through multi-agent system principles. The direction of the marker shows that the intention is to increase human contribution. This does not mean that at production processes human involvement is targeted, however at higher levels of the system or at critical decision points human skills can be benefited.

Second manufacturing system typology is carried out by the decision of customer order decoupling point location. CODP cannot be located in view of the characteristics of production system only. Market characteristics, specifications of the product, transportation issues, competition level etc are all directly affecting factors to CODP decision. However the flexibility of choosing different places to locate CODP is directly related to production system capabilities since most of the constraints to force CODP to be located closer to the customer are imposed by production system incapability. That is to say, if the company is running in an environment where the product variety is quite high but the production system is not capable of converting its production from one variant to another in a short time, this forces the company to produce in large batches in order to reduce total setup time and system down time. Afterwards big batches are stored at end product warehouse and this is a typical make to stock production where demand is met by the products from the end product storage. It embraces both the risk of over production which can turn to be a waste if no demand appears and an opportunity cost rising from early start of the production.

A fully reconfigurable system can relax a considerable portion of the constraints imposed from manufacturing system on moving CODP away from the end product storage towards the procurement of raw material which enables to start value adding activities later in response the demand. Bearing this in mind, *EPS brings radical enhancements on the CODP location flexibility*. Evolvable system capabilities cannot exactly be benefited in one of the classifications explained at chapter 2.3.2. To explain, make to order systems starts the manufacturing and assembly when the customer order arrives and the underlying logic is to customize the product according to the customer wishes. But the product is fixed, the options to choose by the customer are mostly predetermined and the production system is set according

to the main product components. The order, in this case includes specific parameter settings which are chosen by the customer and it is used as an input to start the production and to specialize the product. Assemble to order systems on the other hand are suitable for companies dealing with high product variability. Main components and sub components are manufactured and stored and assembly operation starts with the introduction of the customer demand. This method is applicable if the company does not want to keep end product inventory for each kind of product variants and if the manufacturing of them are long and complicated. And make to stock systems have the risk of costly results coming from forecast errors, early production, inventory costs and such which are already explained in this thesis. All of this MTO, MTA and MTS systems are product specific and can change according to the shifting conditions of the production system, product or demand. They all can be used at an evolvable production system environment and get superior results however the real benefit and breakthrough of evolvable system come into view with the fully reconfigurability which enables ***Invest to Order*** systems (Figure 4-2).

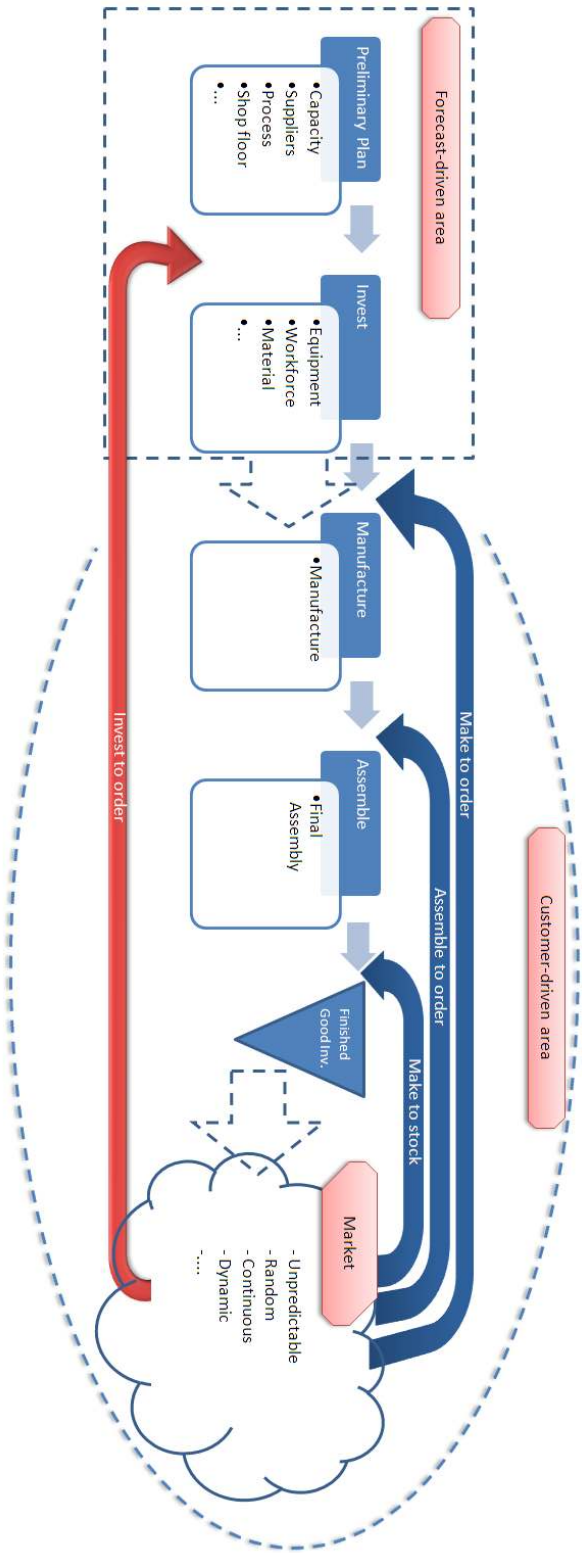


Figure 4-2 Invest to order



In Figure 4-2 there are 2 areas called forecast driven area and customer driven area which differs by the source of the input that trigger the flow of activities. The purpose is to enlarge the customer driven area to avoid the inefficiencies caused by uncertainties. Invest to order system goes one step further comparing to make to order by enabling the customer order to feed the new module and equipment investment for the production system to be reconfigured. This is possible only if you know what modules and processes to invest in order to meet the customer expectation. A sound process planning method is essential at this point and the approach to achieve this obstacle is explained at process planning part of this chapter.

In industry today future market and targeted product scope are determined and investment to the production system is conducted accordingly in order to be prepared responding customer needs rapidly. However this is valid as long as the reality follows the plans. Long setup times and less reconfiguration capabilities of production system prevent to react to new and unexpected requirements coming from the market. Although the current production system might continue being profitable, the lack of rapid response to new requirements will end up high opportunity costs and lose of competitive advantage. Therefore the main challenge for an Invest to Order system is to obtain a production system which allows to be reconfigured not only physically but also from the control and programming point of view. Evolvable Production System characteristics fulfill the fundamental requirements for an Invest to order strategy. At the same time, to be able to conduct a invest to order system, a comprehensive planning reference architecture is compulsory which come into line with the working principles of not only Evolvable Production Systems but also Invest to Order strategy. The proposed preliminary planning reference architecture, called demand responsive planning, is explained in this chapter.

This chapter follows by answering the questions of how does Evolvable Production System reform varying planning phases and how do all these contribute to a Invest to Order system.

## 4.1 Process planning

Process planning is an essential factor in particular for OEMs (Original Equipment Manufacturers). Unless a holistic approach is structured between the capabilities of production system and product requirements; specifications of product will be imposed to manufacturing systems by leaving freedom to product designers and assigning complexity to OEM and manufacturing companies. EPS modules are represented through blueprint files<sup>1</sup> which allow characterizing the settled skills of a module through parameters reflecting also the process capabilities. Since the process capabilities of the available modules are mapped through blueprint files, the product design phase can be fed iteratively until reaching a feasible and efficient solution before designing the production system.

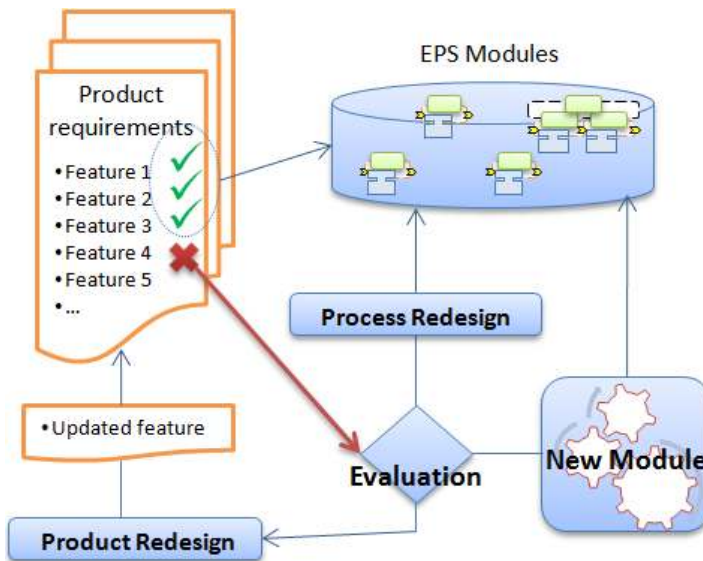


Figure 4-3 Evaluation phase [24]

Figure 4-3 represents the flow of possible actions in the case of a product feature is not possible to be met with the available module capabilities. In the evaluation phase an economical analysis is necessary in order to come to a decision about the

<sup>1</sup> Detailed description and formation of blueprint file is available in the publication of Siltala and Tuokko [33].

way to follow. This analysis is not a straightforward assessment yet it embraces several factors whose weight is changing according to different scenarios. Evaluation holds in itself not only economical valuation but also analysis of technological advancement, life cycle studies and so forth. Product redesign, as one of the outcomes of evaluation, requires revising and updating the product feature in order to fit the available modules. Influencing product design at conceptual phase in order to come up with a feasible solution from the manufacturing view point prevents significant problems to come into being later stages. Another outcome can be redesign of the process in order to harmonize the process with the required product feature. If process or product redesign is not applicable or economical, new module is developed with new process capabilities.

Make to Stock and Assemble to Order manufacturing system are dealing with high product volume, relatively less product variants and long product lives. Since in such an environment new product features are not introduced so often to the market, for MTS and ATO systems, process planning activity attain less attention. The importance of process planning is substantially increasing for Invest to Order system because the process plans are required to be completed in shortest time, meeting customers' needs free from fault and certainly in an economical way. The product definitions might frequently change with small volumes and this imposes compound issues in the production.

## **4.2 Capacity Planning**

Essential inputs for capacity planning activities are forecasted demand pattern, cost of increasing capacity, the benefits of new technology if available, competitor's strategy and feasibility and cost of outsourcing option. The decisions target to maximize capacity utilization. The risk involved in this case to have back orders when the demand exceeds the anticipated demand. To tackle this issue, the widespread strategy is keeping end product inventory to meet excess demand however this holds risks of having obsolete inventory and also brings inventory holding costs. To give a better picture on capacity planning in the conventional systems the following figure elucidates two kinds of capacity decisions. Conventional system in this case represents the systems where the production

system is product dedicated and does not have the competence of reconfiguring itself according to changing product needs in a short time. For such a system, the demand anticipation for the product life should be conducted at the beginning in order to determine production system capacity. If the inventory holding cost is higher in comparison to keeping excess capacity the production system capacity has to aim to highest demand of the product life. The tradeoff between excess capacity cost and inventory holding cost is the determinant factor on setting the intersection point of product life and system capacity in Figure 4-4.

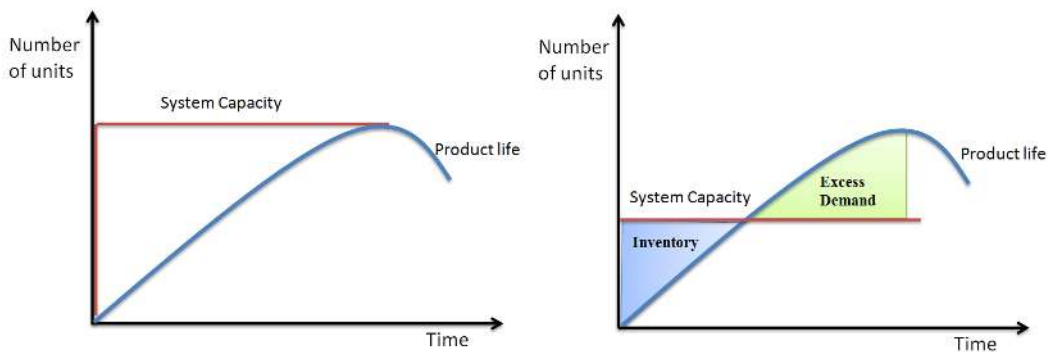


Figure 4-4 Capacity planning in conventional systems

The common difficulty for capacity planning of conventional systems is requirement to anticipate demand before the investment to capacity. Evolvable production system, tackles this issue by providing fully reconfigurability through process oriented modular structure based on multi agent based control. This offers the possibility of delaying capacity investment (invest to order) since the system setup time is minimized or even eliminated. The obligation of forecasting product demand pattern for a long term can be relaxed and the risks involved in forecast errors can be avoided through EPS.

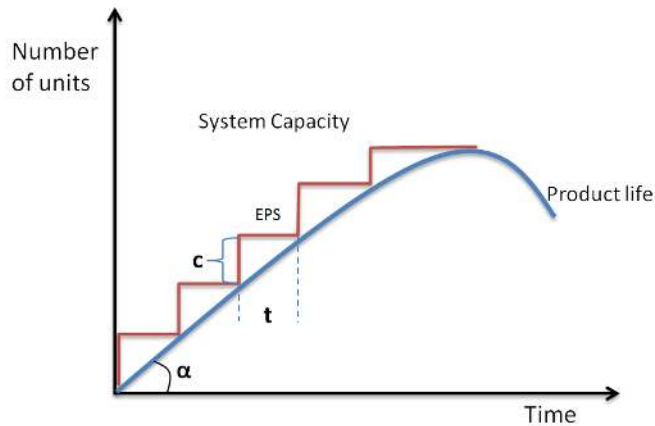


Figure 4-5 Capacity planning in EPS

Figure 4-5 shows how EPS can be utilized through incremental capacity planning. Instead of investing on capacity relying on long product life forecasts, the time to be forecasted can be minimized and the capacity can be extended in response to increasing demand incrementally. In the figure the parameters used are following,

$c$ , capacity increment

$t$ , targeted time period

$\alpha$ , slope (product pattern parameter)

Capacity increment in this case is a multiplication of targeted time period and the product pattern slope.

$$C = t * \alpha$$

It is important to highlight that the cost parameters have to be integrated to capacity increment decision which is one of the targeted work of further research. Capacity decisions for EPS needs to be supported by analysis to reach a optimal result on the tradeoff between inventory holding cost, excess capacity, customer backlog cost etc. So that the capacity and product life intersection points as shown in Figure 4-6, is optimized.

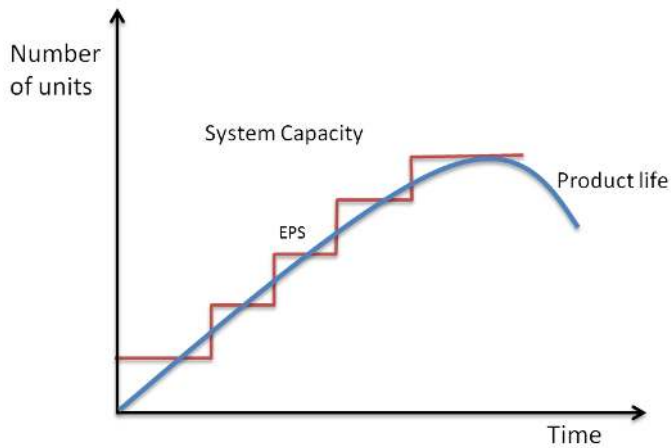


Figure 4-6 EPS capacity planning decision

### 4.3 Material Planning

Material planning activity is supposed to supply the required material in the shop floor at right time, right quantity, right type and to right location. It requires coordination of complete cycle of material and the associated the flow of information. It covers the materials' (1) identification, (2) cataloging, (3) standardization, (4) requirement determination, (5) procurement, (6) inspection, (9) quality control, (10) packaging, (11) storage, (12) inventory control, (12) distribution, and (13) disposal.

The way to move material through MRP system is explained at chapter 2.5.1. Since it is a concrete plan and not dynamic to respond unexpected changes, it cannot be an option for a shop floor which is structured by Evolvable System architecture. Whereas a pull based material planning as in the JIT philosophy (Chapter 2.5.2) can harmonize itself with the requirements of EPS shop floor. The infrastructure to apply JIT principles into a production system requires having a short setup time together with a limited number of product variants. Information flow plays essential role which is conducted through kanban cards. EPS multi agent control architecture allows exchanging messages between every entity on the shop floor which can

provide an efficient way to conduct flow of information. To be clearer, an inventory area which is supplying subcomponents for assembly line can send a message to material planning unit when the level falls below a critical level. The flow of information should harmonize itself according to the methodology to conduct material planning. There is a need of 2 methodologies for production environment, one is for the material transfer from material inventory to production system and the other one is for the transfer to replenish the material inventory from the suppliers. There are methodologies in the literature such as Economic Order Quantity, (Q, R) systems etc. however there is a potential research area for this in order to integrate the available methods to multi agent control based shop floor or to generate new methods. This area need further research in order to generate feasible means to a multi agent system structure.

#### 4.4 Demand Responsive Planning Model

Demand Responsive Planning (DRP) is a preliminary planning reference architecture for Evolvable Production System which targets to systemize the planning activities by creating logical relations between them in a feasible structure to a fully reconfigurable production system. The problems arising at planning activities due to varying reasons as explained in the thesis are targeted to overcome through a comprehensive planning reference architecture which is harmonized with the characteristics of EPS in order to gain advantage in an efficient way. It is important to address that this reference architecture does not cover the efficacious methodologies in itself however it points the missing methodologies specifically at different places.

There are different representation blocks of functions and activities in DRP which are shown in the following figure.



Figure 4-7 Model blocks

Main activities characterizes not only planning activity, it might include a physical activity e.g. system reconfiguration. The sub-block stick to main activity signifies the functionality covered by main activity. The framed block embodies the actors or stakeholders. In the model, the spots where a specific methodology is necessary are shown in the shape of the blocks named required algorithm/method as in Figure 4-7.



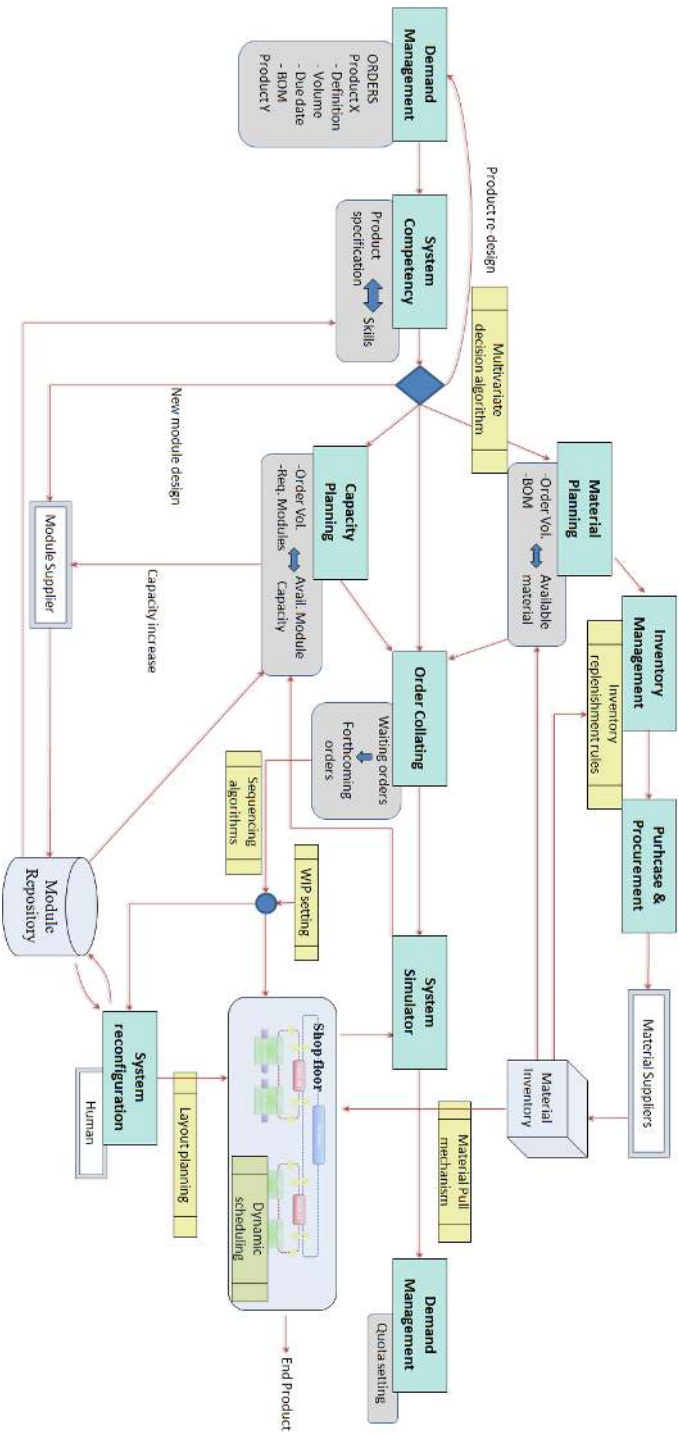


Figure 4-8 Demand responsive planning

Demand management block in the model is the one which has the connection to customers therefore through demand management the introduction of the order to the planning system is performed. Demand management is conducting customer relations from the arrival of the order until the delivery. The information passing into the system is classified under 3 main titles, namely the definition of the products included in the order, the volume and the due date. Product definition includes the information about product structure namely bill of material which show the type and quantity of components building the product and also the hierarchical relationship between them (Figure 4-9).

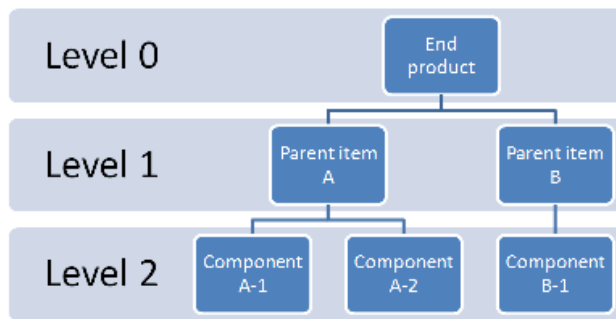


Figure 4-9 Bill of material

Product volume has the data on the quantity of desired product on level 0 at bill of material. Varying on the industry and product types in some cases the due date can be imposed by the customer or a due date quota can be asked from the company.

Next step after the order is arrived is to analyze if the production system has the capability to meet the product specifications. System competency block includes the functions in itself which are described in process planning at chapter 4.1. That is to say the essential thing to check is if the skills are eligible to meet the required product features through available modules in the module repository. If not, the product design can be revised as long as it is an option and feasible. Otherwise the new module requirement needs to be submitted to module supplier with the required product specifications. A cost analysis in this phase is necessary in order to choose the best alternative.

Once the availability of the skills is ensured to handle the product specifications, the order proceeds with 3 activities in parallel which are material planning, order collating and capacity planning (Figure 4-10).

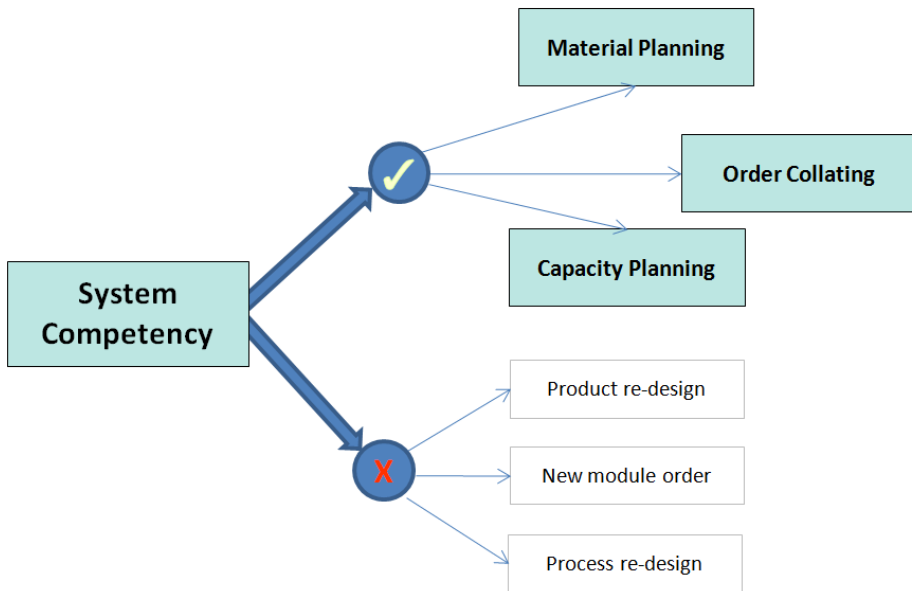


Figure 4-10 System competency

To start with material planning, this activity has the function to check if the required materials exist. The input required for material planning block are BOM and order volume. With the help of the BOM the types of the components required to fulfill the products in the order is obtained and also the volume information is available. By a straightforward calculation, the multiplication of the volume and the components of the products, the figure about the material need is obtained. The match between the available materials stocked in the material inventory and the required material results in one of the ways showed in the following figure.

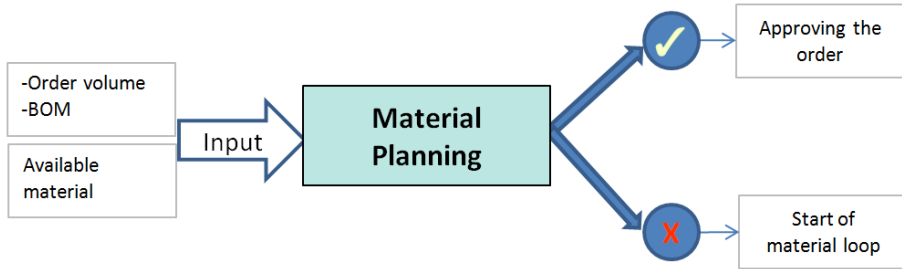


Figure 4-11 Material planning

The order is approved from the material requirement point of view when the components are available in the material inventory. The approval is sent to order collating block which represents that the production of the order can be conducted without any lack of material. If there is missing components or not enough quantity of any component the material loop is initiated by material planning block to obtain them (Figure 4-12).

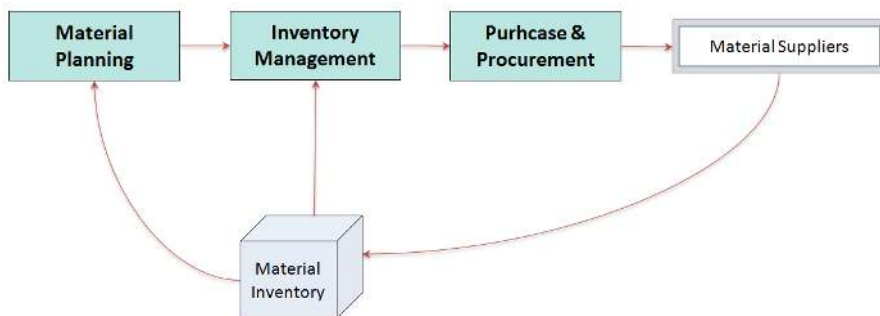


Figure 4-12 Material loop

The main function of the loop is to supply the material to production system in the shortest time. The role of Inventory management block is to monitor inventory levels and to follow the inventory replenishment rules. The efficient and economical way of inventory management is conducted by the method designed in order to keep the material quantity at optimum level in the inventory to prevent delay caused by material supply and also to prevent extra costs caused by inventory holding. Current reference model does not encapsulate a methodology to

accomplish this target. According to the rules of the inventory replenishment the purchase and procurement activity is supposed to generate the material orders accordingly. It is essential for the determination of an eligible methodology to analyze the critical materials and components which have long lead time to arrive. Time, quantity and specifications of the material orders, safety stock quantities are the fundamental outputs of the method. Supplier evaluation and management are not explicitly shown at RDP sketch however it is essential to systemize the relations with the suppliers to harmonize the work and to optimize material supply.

There is one critical point which needs to be highlighted about inventory management. One of the main purposes of the Responsive Demand Planning model is to minimize dependency to forecasts on the planning activities. Inventory management activity on the other hand is targeting to keep materials in the inventory to supply when it is needed. Without arrival of order, the needed material cannot be known beforehand. If the material order is given when the product order is arrived, it can already be too late. That's why inventory replenishment methodology at this phase plays crucial role in order to achieve the system target.

Capacity planning activity controls the availability of the modules from the quantity point of view in comparison to needed volume of products. After the skills are analyzed in the system competency, capacity planning block checks if the module repository has enough modules to deliver the order on time.

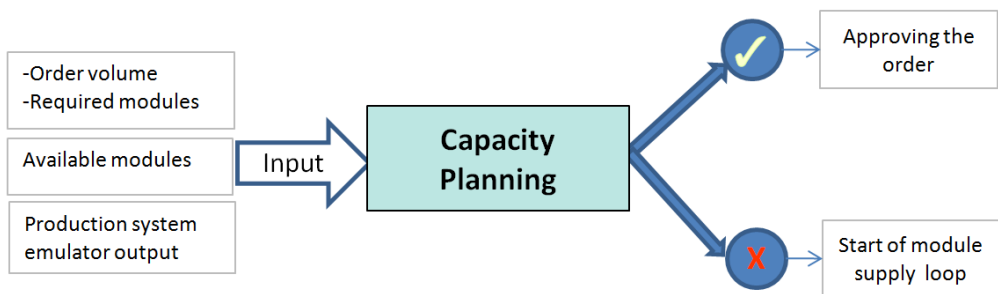


Figure 4-13 Capacity planning

If the output of the comparison has positive result then the order is approved and sent to order collating block to confirm that from the capacity viewpoint there is no limitation to start production. If the result concludes that there is a lack of module to produce and deliver the order sticking to due date, module supply loop is initiated in order to increase the capacity of required processes (Figure 4-14).

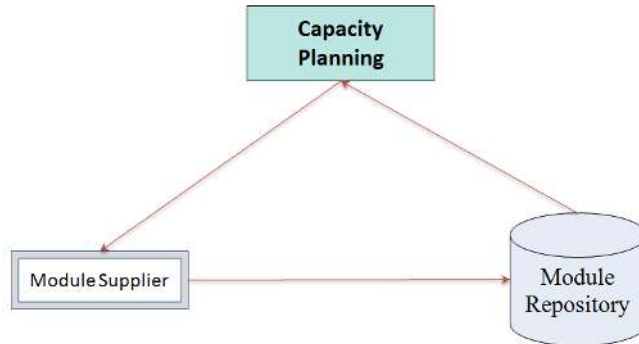


Figure 4-14 Module supply loop

Considering the shop floor of evolvable production systems, the flow of product and processes are not designed specifically to optimize the product flow through the system as in the dedicated lines. Therefore for none of the products there is a fixed throughput time. Depending on the mix and quantity of products that are on the queue to be produced or on the shop floor being processes, the throughput time can show considerable variations from product to product. Concerning the capacity planning activity, it is supposed to have a figure in order to compare the time of order completion with the available production capacity, with due date. This necessity can be provided by the system simulator which is able to execute the behavior of the production system with the available workload in order to generate the throughput time for a specific order. This output is the essential input for capacity planning activity.

Order collating block is the seizing block of order before introduced to production system. There are 2 sets in this block which are named as waiting orders set and forthcoming orders set. Orders passed to order collating block are directly added to waiting orders set. Once the material planning block and capacity planning block

approves the order from material and capacity point of view the order at waiting order set can be release to forthcoming order set. This is when the product agent is initiated in EPS.

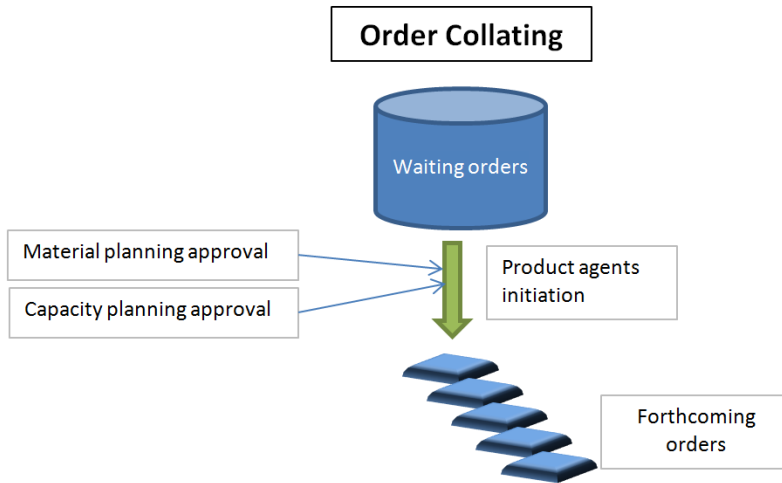


Figure 4-15 Order collating

The main reason to hold the orders without releasing directly to production system is to prevent stops during run time due to lack of materials or components which brings about delaying other products to be completed. Hence, release of the orders to forthcoming orders set indicates that,

- Information arrived from system competency block approves that the process capability is available to meet the product specifications in the order. To be clearer, an order which has an unmet product specification, or a rejected order due to being unprofitable is not transferred to waiting order set. All the orders in this set are already approved from the process capability point.
- Material planning block approves that the components and materials required for the specified order are available to be pulled from the inventory
- Capacity planning approves the required quantity of modules are available.

Product agent initiation does not necessarily mean that the production starts immediately. There is another control before the product agent is launched to production system which is WIP setting rules. This characterizes the buffer rules in order to keep the production environment under control for the purpose of optimizing WIP inventory level. If WIP level is kept high, the resource utilization can be kept high however it will increase throughput time. Less WIP is better as far as fast response to changing situations is concerned. The main challenge for WIP setting is to adjust parameters in a high product mix environment. The methodology which is needed at this stage requires handling these issues.

After the product agents are created the sequence to launch to production system has to be conducted dynamically through negotiation among the agents in order to find the best sequence. Sequencing algorithm which is required at this point has to be compliant to multi agent structure and should carry out sequencing dynamically without a central controller. The result of this algorithm should embrace efficient solution considering both the due date constraints of orders and also the system reconfiguration requirement. Although system reconfiguration time is so short, considering the material supply to the production system batching of similar products would bring advantage by decreasing the product mix and complexity on shop floor.

In EPS there are different kind of changes which might be required for an order to be conducted and they are explained in [34] as;

- Level 0: Parametric Changes – adapting the behavior of available capabilities; e.g. changing the force settings of a pressing device.
- Level 1: Logical Changes - adapting the utilization of available capabilities (skills); e.g. change of process sequences from one product to another
- Level 2: Structural Changes – adapting the available capabilities; e.g. changing one process module for another one or adding an additional assembly station.



In the case of a level 2 change requirement the layout of the system will be modified. Layout planning rules are supposed to be integrated at this phase in order to optimize layout creation process. The location of the stations and processes are essential for the efficiency of flow of product through the system, buffer rules, transport agent efficiency and so forth.

System simulator module has the function of duplicating the behavior of the production system in order to figure out the throughput time for a product agent to pass through the system. This information is fed to demand management and capacity planning blocks. System simulator has all the order information collected at order collating block, the current resources and layout of production system and also the module data at module repository. Demand management might need this information if there is a need to set quota for the order. It is essential to give the shortest possible time in quota setting to gain competitive advantage.



## 5 CONCLUSION AND CRITICAL REVIEW

Architectural characteristics of EPS bring key advantageous considering the shop floor efficiency on specific domain which can be benefited with proper planning approach. To reach a preliminary planning model, the impact of EPS on shop floor and on planning strategies has been enlightened from process planning, capacity planning and material planning point of view. This created the foundation to build a holistic planning model called demand responsive planning. On this standpoint the given model targets,

- to decrease the dependency on forecasts with the agility of shop floor to changing product requirements,
- to harmonize the material needs and capacity needs in accordance with the available and/or promised orders,
- to prevent extra and early investment to material which has the risk of; becoming redundant with changing conditions, bringing additional material holding cost and opportunity cost,
- building the planning framework for investing to required process capabilities with introduced demand from the market by a coherent flow of planning activities,
- to enable cooperation across the stakeholders on the value chain of the product.

Manufacturing planning and control systems are in deep need of accurate approximation of market conditions to configure the system properties accordingly. As long as the main focus area stays on prediction of future states, the results will include randomness in itself as in the nature. The essential problem is the lack of rapid reconfiguration of production system to altering circumstances and requirements. Once this breakthrough is achieved on the shop floor as EPS, the planning systems remain inadequate to benefit improvements brought by rapid reconfiguration at different planning levels. A complementary approach of production system reconfiguration and planning methods follow a factual principle

which is “*optimize over time not for any given state*”. Supporting notion of this principle is the reusability of the modules which are dedicated to process specifications and adaptiveness of the whole system not only by physical reconfiguration but also through multi agent architecture by control system adaptation without reprogramming effort. Product dedicated production systems which have specialized equipment according to a class of products, are in the risk of becoming obsolete depending on the life time of the product whereas the processes stays and the equipments can be reused even if product requirements varies. Hence, the lifelong reusability of the modules bring advantage on the long term by being utilized for different configurations.

By means of EPS advancements on shop floor, the existing characteristics of manufacturing planning and control system require to shift from dealing with the unpredictable environment with the intention to create a set environment through accurate forecasts, to coordination and cooperation of stakeholders who are accommodated across the value chain of the product from the conceptual design to the delivery of the product. The approach which is called co-opetition [35], cooperating to create a bigger business pie while competing to divide it up, reflects also the essential requirements of cooperation.

From the application point of view, as emphasized in the thesis planning reference architecture is still at the preliminary phase. Demand responsive planning has the function of providing a coherent architecture to be applied at different domains. An analogy between EPS reference architecture and system architecture (These concepts are explained in chapter 3.4 Operational Working Principles) can be conducted to clarify the function of the planning reference architecture. Through the methodologies integrated to planning system, domain specific planning structure (planning system structure) can be constructed. In the available planning reference architecture, the locations of the methods to be applied are specified and they are named as follows,

- Multivariate decision algorithm, after the system competency block to evaluate the alternatives on the way to achieve a proper match between product specification and processes,

- Inventory replenishment rules, which is a part of inventory management and serves to systemize efficient inventory structure,
- Material pull mechanism, which coordinates the relation between the shop floor and inventory according to changing product mix which needs to be in synchronization with order collating,
- Sequencing algorithm, which needs to be compliant to multi agent based control architecture,
- WIP setting, depending on the shop floor and layout characteristic, WIP setting rules may vary,
- Layout planning, the method applied at this point should result in efficient layout solutions in order to optimize the flow of product agents on the shop floor taking into account the workflow of available orders and WIP settings,
- Dynamic scheduling, the allocation of available jobs to appropriate resources are conducted dynamically thanks to multi agent system characteristics.

As far as the further research is concerned, as explained in the research approach the model is targeted to be detailed as next step and investigated for possible improvements and application problems. Shop floor studies and examination will be possible to be tested on a project demonstration which is under development today in the scope of a European project called “Instantly Deployable Evolvable Assembly Systems (IDEAS)”. A sample planning system architecture derived from the Demand Responsive Planning reference architecture is targeted to be formed and evaluated in order to validate the approach on a test case. Obviously on the test case environment only shop floor performance of applied methodologies can be evaluated.

Namely, the research questions for the progression of the research are as follows,

**RQ-1** What structural impacts and advancements to MPC framework does an EPS shop floor bring forth on the way to achieve demand responsive production?

This research area is expected to generate an extended and quantified version of what has been introduced in this thesis to validate the arguments.

**RQ-2** How can Demand Responsive Planning be improved to-obtain an approach across the companies included on the value chain of the product? (how to effectively apply co-opetitive strategies)

To be more specific, this research question is targeting to explore how to increase the efficiency of the capacity planning loop and material planning loop at DRP.

**RQ-3** How the specification and requirements of the methods is identified to be applied in DRP compliant with the multi agent based distributed control environment?

This area is aiming to identify the specifications for methods to be applicable to DRP and also the requirements from the agile planning point of view. This will help to generate planning system architectures out of the planning reference architecture (DRP) by integrating the appropriate methods.

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