**UNIVERSITY OF VAASA**

**FACULTY OF TECHNOLOGY**

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# IMPLEMENTING MASS CUSTOMIZATION

USING SAP VARIANT CONFIGURATION AND A 3D PRINTER

Master's Thesis in

Industrial Management

**VAASA 2014**

**TABLE OF CONTENTS** **PAGES**

**LIST OF FIGURES**

**LIST OF TABLES**

**ABBREVIATIONS**

3-D – 3 Dimensional

SAP VC- SAP Variant Configuration

MRP – Material Requirement Planning

BOM – Bill of Materials

DDB – Dynamic Database

SD – Sales and Distribution

PP – Production Planning

LO – Logistics

ERP – Enterprise Resource Planning

EMC – Engineering Change Management

OCM – Order Change Management

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| **MAJOR SUBJECT:** | Industrial Management |
| **YEAR OF ENTERING UNIVERSITY:** | 2011 |
| **YEAR OF COMPLETING MASTER'S THESIS:** | 2014 **PAGES:** 83 |


## ABSTRACT

The process of manufacturing customized products at the efficiency of mass production is called mass customisation manufacturing. In order to implement mass customisation a product configurator, a well-planned configurable product platform and a flexible manufacturing technology are essential. As 3D printers are becoming more and more popular it is evident that they act as very flexible factories that could manufacture any object. This thesis tries to find out how 3D printers and product configurators could be combined to implement mass customisation manufacturing. The system created in this thesis manufactures configurable motorcycles whose configuration model is maintained in SAP-ERP system. A product configurator built using SAP Variant configuration allows the user to configure a variant of the motorcycle according to their needs using the configuration model. This configured variant is manufactured using a 3D printer. Qualitative methods are used to gain knowledge and understanding about mass customisation and SAP Variant configuration from books, scientific articles and software development forums. Using this knowledge the system is implemented which could manufacture approximately 23 different types of motorcycles customized by the user. The users who configure and manufacture the motorcycles also get hands-on knowledge about basic business processes in SAP ERP related to production planning (PP) and logistics (LO) modules and understand how information flows in the ERP system with respect to mass customized manufacturing.

KEYWORDS: Mass Customisation, Product configurator, 3D Printing, SAP Variant Configuration, Configurable products

## 1. INTRODUCTION

The concepts of mass customization and product configurators have been extensively studied in the past years. Stanley M. Davis termed the phrase mass customisation in 1987 in his book titled Future Perfect. Anderson-Connel, Ulrich & Brannon (2002) mentions that, the word mass customization is an oxymoron that symbolizes a mix of the ideas of both mass production and customization. Mass customization is a method to manufacture products customized closer to the needs of the customer, at a price and speed close to that of mass production. Pine (1994) states that a new paradigm in management is emerging which understands that every customers need is different and fragments homogenous markets into heterogeneous ones and tries to create non-standardized products close to the customer's need. Svensson and Barford (2002) claim that "*for more than 20 years mass customization has become the buzz word and has become the standard in many industries*". Today mass customization has become so popular that Gandhi, Magar and Roberts (2014) state customers are able to customize products that are used every day in their lives for example mobile phones, cars clothes etc.  In current market turbulence, predicting the demand for a particular product is uncertain. Simchi-Levi, Kaminski, & Simchi-Levi (2007) state that demand forecast is never accurate. Therefore, it is constructive to know the customer's need and to manufacture a product close to it.

In order to make a product close to their needs, companies let the customers configure the product they are about to buy according to certain configuration rules. This type of production is called customer order driven production and the products are called configurable products. A product configurator enables a customer to configure a product according to his needs. In other words, a product configurator acts as the interface between the manufacturer and the customer. In order to obtain a balance between volume and variety configurator should contain certain rules that limit the variety of the product. If there are no rules for configuration every customer would demand for a completely new configuration and the level of customisation gets closer to full customisation. Tiihonen and Soininen (1997: 3) state that, a configurable product is predefined to meet only a particular range of customer needs and is composed of pre-designed modules that are arranged according to a pre-designed architecture. They also argue that during sales it doesn't require any new or creative designing work to generate a final product specification and every final specification generated during a configuration process is tailored to meet an individual customer's need. As Bertrand, Wortmann and Wijngaard (1990: 145-145) argue, the information systems for customer order driven production are structured by having the customer order as the central part. Here customer order forms the basis for the work order whereas in make-to-stock production a work order could be placed independent of a customer order. The authors also mention that in customer order driven production information like the bill-of-materials, routings and activity networks are available independent of customer orders and the importance of Bill-of-materials decrease as the level of customisation increases and the production method moves from make-to-stock to engineer-to-order production.

Traditional manufacturing systems has been developed mainly having mass production in mind (Tuck, Hague, Ruffo, Ransley & Adams, 2008: 245-258) which is based on economies of scale in order to increase profits and may not be suitable for mass customization. Since mass customisation allows varieties in the products the company's manufacturing method should also be flexible enough to manufacture that variety. Tuck et al (2008)., mention that rapid manufacturing is based on additive manufacturing where the product is manufactured by adding layers on top of each other as opposed to traditional manufacturing where manufacturing is done by subtracting or removing layers from a block of raw material. 3D printing technology is also based on additive manufacturing. The economist (Nov 22: 2012) mentions that in additive manufacturing "*Designs can be quickly changed, so the technology enables flexible production and mass customisation*". Petrick and Simpson (2013: 12-16) argue that with technologies like 3D printing and additive manufacturing industries may not require high volume manufacturing to obtain profits rather economies of one production is sufficient.

Not much research has been done trying to put a 3D printer and a product configurator together to implement mass customization. Hence, it would be of my interest to learn how to create a product configurator using SAP VC and combine it with a 3-D printer to demonstrate mass customization manufacturing. Hence, this thesis tries to find a solution to integrate a product configurator with a 3-D printer, as the product configurator helps managing a configurable product and the 3D printer acts as the factory. It also demonstrates mass customisation manufacturing and how the information flows within the ERP system in this manufacturing context. A simulation model is built using the software ExtendSim and the production capacity of the factory/3D printer is estimated. The resultant mass customization manufacturing environment created in this thesis will be called the simulation/demonstration system. Any user involved in this simulation could get hands on knowledge of using SAP ERP system and a product configurator while gaining basic understanding about 3D printing technology.

## 2. METHOD

This thesis uses qualitative research methods to explore and understand the concepts of mass customization and product configuration and tries to simulate mass customization manufacturing. Rest of this thesis is divided into theory, empirical, and results & discussion, parts. The theory part contains information and results from previous research about 3-D printing technology, mass customization, product configurators and the order fulfillment process. It also includes information and instructions about how to implement a configurator using SAP Variant Configuration. The empirical part contains step wise procedure and screenshots of how the sales configurator is developed and how the configured product is manufactured using the 3D printer. Finally the results and discussion section contains the procedure to simulate mass customisation manufacturing as implemented in this thesis and also explains the key findings, future research possibilities and limitations of the thesis. Figure 1 explains the theoretical framework of the complete thesis.

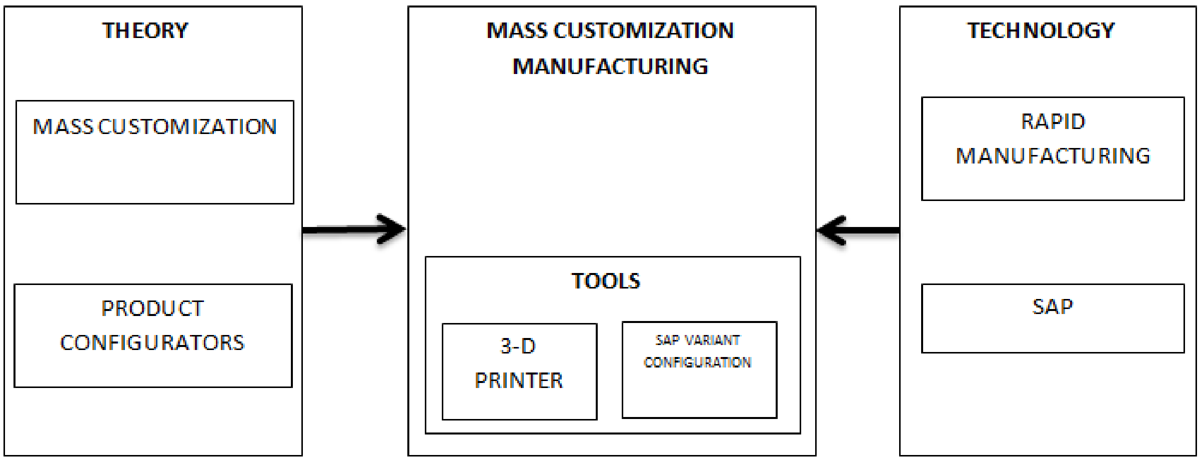



Figure1: Theoretical framework of the thesis

The main research problem is broken down into sub problems in order to de-magnify it and to arrive at the solution effectively.

Main problem:

> How to combine a Product configurator with a 3D printer and simulate mass customization?

Sub problems:

1. How to develop a product configurator?
2. What connects the product configurator and the 3D printer?

Technologies like rapid manufacturing and SAP provides the environment for the demonstration system by providing tools like 3D printer and SAP Variant configuration. Designing the product configurator follows one of the seven strategies studied by Haug, Hvam and Mortensen (2012: 471-481). This strategy was chosen because of its simplicity and as the authors mention it may work well if the number of persons involved in the development of the configurator is minimal and they have both the required product knowledge and the configurator software skills. In this thesis, I have designed the product structure and will convert the product structure into a configuration model using SAP Variant Configuration. Developing this product configurator will be the solution for the first sub-problem.

Tiihonen and Soininen (1997: 6) have generalized and compiled the possible steps that could exist from sales until delivery of a configurable product in the form of a process. They state that customer requirements are the inputs to this process which are converted into a valid product specification with the help of a configurable model and then delivered as a final product back to the customer. Furthermore they mention, although this process contains 2 stages of configuration one for sales and one for engineering respectively, in some scenarios one stage of configuration might be sufficient and a few other intermediate tasks might be added to the entire process. This order delivery process will be executed by using the 3D printer as a factory that manufactures the components to the final product. Developing the order delivery process will be the solution to the second sub-problem. The solutions to both the sub-problems, put together will provide the solution to the main research problem. Figure 2 illustrates the framework of how the demonstration system is developed.

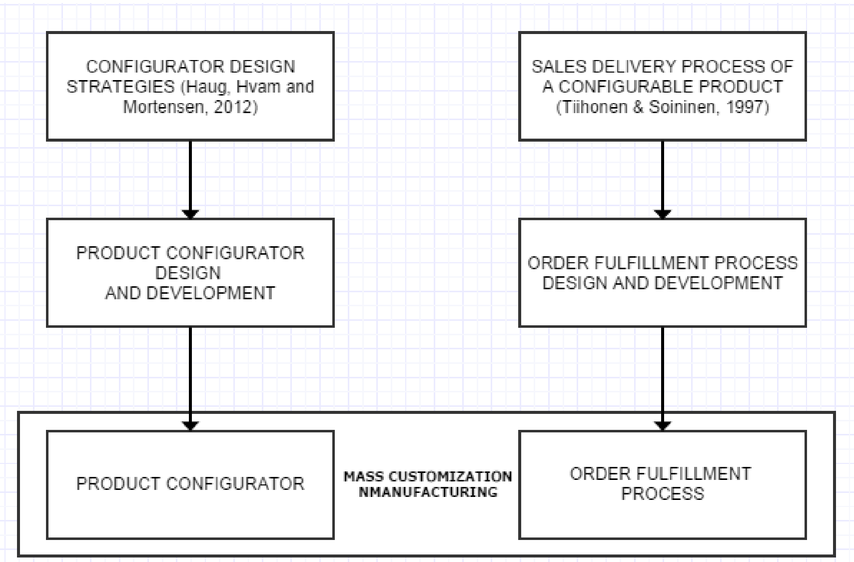



Figure2: Simulation development process

The solution for the main research problem created in this thesis is a simple simulation which could be done by one person. Complex and more sophisticated solutions to the problem might exist, but since my interest is to get more familiarized with product configurators and SAP Variant Configuration the main focus of this thesis lies on these areas. Because of my limited knowledge in 3D modelling 3D models used for manufacturing the components for the final product are downloaded from the internet. The website www.thingiverse.com and the search engine www.yobi3d.com are the main web repositories from where the 3D models have been searched and downloaded.

# 3. LITERATURE REVIEW

## 3.1. MASS CUSTOMIZATION

### 3.1.1. DEFINITIONS:

Mass customization is a powerful business concept that manufactures products close to the needs of the individual customer at a cost competitive to mass production. As Svensson and Barford (2002) describe, the market of mass customization is produced by finding a balance between the effectiveness of mass production and the individualization of traditional craft production. Figure 2 describes this concept.


Figure 3: Mass customization as a combination of mass production and customization (Svensson & Barford, 2002)

Hart (1995) defines mass customization in the following two ways namely visionary and practical definition:

Visionary definition: "*the ability to provide your customers with anything they want profitably, any time they want it, anywhere they want it, any way they want it.*

Practical definition: *the use of flexible processes and organizational structures to produce varied and often individually customized products and services at the low cost of a standardized, mass production system" (C.H.L. Hart, 1995: 36).*

### 3.1.2. MASS PRODUCTION - THE PREDECESSOR

In the latter half of nineteenth century England was feared to lose its dominant position over manufacturing as America started overtaking them. The reason for this is that, American system of manufactures focused on factors like technology, process and machinery used for production, the skills of the workers, interchangeable parts, and strived to continuously improve these factors. Beginning in the late 1800s till the early 1900s a similar but new system of manufacturing evolved which is known as mass production. This system inherited some characteristics from American system of manufactures but added certain new principles to it. The key principle is *flow* which defines the automatic movement of work from one work station to the other once when the work is over. This principle defined the system of mass production just as the principle of interchangeable parts defined American system of manufactures. Mass production focused on economies of scale while the products were highly standardized with low cost and price. (Pine, 1993:4 - 52)

For homogenous markets were the demand was easily predictable mass production was found suitable and it manufactured products with low cost and fixed quality. The life cycles of mass produced products were long with long product development cycles (Pine, 1993). The main drawback of mass production is the lack of variety in products. It costs more to produce variety, since reducing cost is a main aim of mass production usually the number of variants were minimum, either one or two.

CONCEPT OF MASS CUSTOMISATION:

According to Pine (1993) mass customization is a system in which variety and customization replaces standardized products, product life cycles and development cycles are reduced drastically. The author also argues from a business point of view mass customization serves individual user's needs and creates more customer satisfaction, but the manufacturing processes should be flexible enough to produce more varieties at a nominal price thereby meeting individual customer needs to improve customer satisfaction. Additionally Pine (1993) also mentions that this system fragments a single big market for one product into numerous small markets for much variety of products. Another way of defining mass customization could be to "*provide every customer with a product that matches his/her unique specifications*" (Eastwood 1996: 172).

Lampell and Mintzberg (1996) claim that mass customization is sub-divided into three types depending on the level of customization offered by the manufacturer. The following picture explains the different segments of manufacturing as explained by the authors between pure standardization/ aggregation and pure customization. The first and last segments in the picture namely pure standardization and pure customization are omitted from discussion since they are not relevant to this thesis work.

In segmented standardization firms collect the needs of customers into clusters and then respond to these cluster needs, thereby narrowing the features of the product. In customized standardization customers are given a range of standardized components and are allowed to customize a product from those components which are assembled to order later, hence, in this phase the assembly and distributions steps are customized but not the design and fabrication steps. An example for customized standardization is automobile manufacturers. In tailored customization a product can be customized to a customer's need right from the design phase. This phase is also called as modularization or configuration. In tailored customization, a model is shown to the customer and then adapted to his/her needs. An example of tailored standardization is suit tailoring. (Lampell and Mintzberg, 1996)

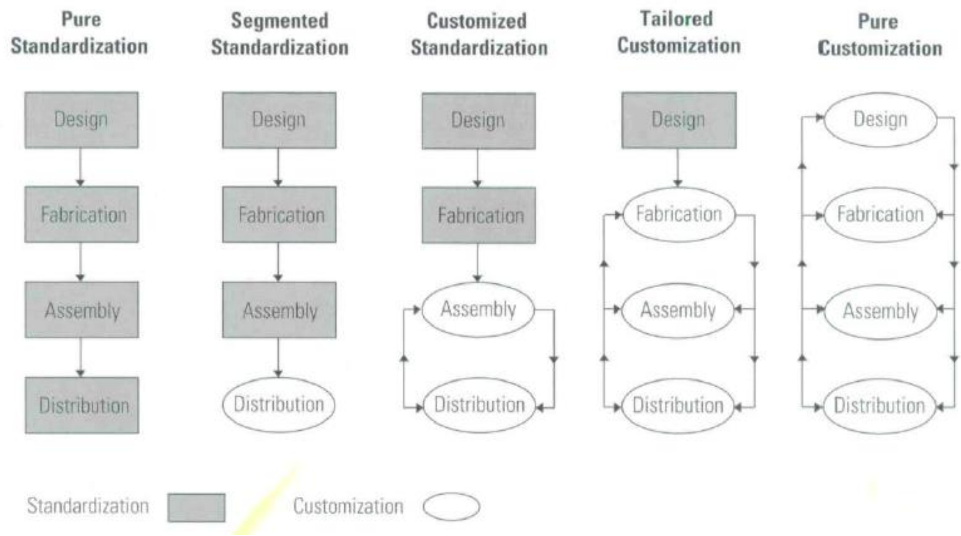



Figure 4: A Continuum of strategies, (Lampell and Mintzberg, 1996).

Hart (1995) has created a framework for companies to analyze themselves on how ready are they to enter mass customization strategy. Pursuing mass customization strategy before this analysis is as he explains "*venturing into literally uncharted territory*". According to the author the first pillar of the framework known as the *customer customization sensitivity* talks about two factors one is how unique is the customers' need and the other one is how much of those needs are not fulfilled by the products in the market. This gap in satisfaction of customer needs is named *customer sacrifice* by Hart. Additionally Hart (1995) mentions that most importantly a company needs to understand if their customers care for customization at all. This customer sacrifice and the uniqueness of his/her needs are directly proportional to the customization sensitivity. Along with these, Hart also argues predicting how much the market will grow in terms of size is essential before making decisions about profit potentials. Under customer customization sensitivity the author mentions that a product's variety should be only inside the *envelope of variety* i.e. a products variety should only be inside the areas where customers truly need it. Variety is a tool for achieving customization and the value added by variety should exceed the extra cost demanded for customization (Svensson and Barfod, 2002:

77-89). Marketing also plays a major role when it comes to mass customization, as Hart argues in an effective sales presentation the customer needs to see only what they wish to see.

The second pillar in this framework is called *process amenability* this process explains what factors could enable mass customization, what strategy should be used and how products should be designed, produced, marketed and distributed. A company needs to know beforehand if mass customization enabling technologies are available in the market and how much would it cost. Hart mentions these analyses should not be started with cost cutting in mind. Along with technological enablers an organization needs to motivate their own employees by methods like paying for employee performance, and creating self-directed work teams. Marketing and design teams of an organization should have access to all data and information to create customized products and also the ability to analyze that data. According to Hart, it is beneficial to reduce the intermediaries between an organization and its customers in order to create effective mass customization. The design team should have a fast and flexible process to transform customer needs into useful info and the ability to develop and support "envelope of variety". It should be noted that the production and distribution process of an organization should be flexible enough to support mass customization. (Hart, 1995: 36-45)

Hart (1995) has named his third pillar as *competitive environment* and has explained it in the following way. First of all, an organization should know well about their competitors in market, the market turbulence, credibility of their organization, the loyalty of their customers, and their position in the market place. The author also mentions that any organization that makes the first move towards mass customization in the market has the advantages of creating an one-on-one relationship with the customer, engaging in individual dialogue with the customer and making that relationship a true knowledge gathering experience about customer requirements and using that knowledge to track and fulfill individual customer's needs. Finally under the pillar *organizational readiness* Hart explains that an organization's leader and strategists should know the core capabilities of the organization by analyzing its attitude, culture, resources and knowing how ready it is to take advantage of mass customization. The author concludes this framework by saying an organization and its strategists and leaders should be open to change.

### 3.1.3. ENABLERS AND CHALLENGES OF MASS CUSTOMISATION

Real catch in mass customization lies in creating economies of scope as opposed to economies of scale in mass production. As the cost of creating product varieties are always high, mass customized products come with a premium cost. As measuring product demand becomes more difficult with the increase in variety, mass customized products are usually manufactured-to-order which will also take a considerable lead time, as opposed to mass production where demand forecasting is comparatively easy and products are manufactured-to-stock and hence available all the time.

According to Svensson and Barfod (2002: 77-89) generally mass customization manufacturers will face two kinds of threats one is external and the other internal. The internal threat comes from within the organization in the form of cost and lead time (Eastwood, 1996: 171-174) the external threat comes in the form of competition where other manufacturers could provide the same customization for a higher quality and lower cost. Furthermore the authors also mention mass customization may have different drawbacks for different actors in the supply chain and understanding customer needs is a problem for all actors in the supply chain. Shugan (1980: 99-111) argues that consumers face a problem in choosing a product when a range of varieties are offered to them. He also mentions some strategists thought that increasing the varieties would help the consumer in making better and easy decision but that in turn increased the problem in choosing.

Zipkin (2001: 81-87) explains in brief the challenges along the entire supply chain that companies might face when it comes to mass customization strategy. He has collected the challenges in an organization into 3 broad processes namely information gathering, manufacturing and logistics and only if these 3 processes function flawlessly both individually and also collectively in an inter-organizational supply chain then mass customisation will work fine for the organization. He also classifies 3 building blocks of mass customization as "*elicitation, process flexibility and logistics*" which corresponds to the three processes information gathering, manufacturing and logistics respectively.

Elicitation is the process of discussing and obtaining necessary information from consumers. Information like consumers' name and address, the choices that they choose generally from the variety offered, in some cases their physical measurements and customer's reaction to prototypes are collected during elicitation. Internet based technologies, 3D modelling and designing, and other software tools like a product configurator are used for elicitation. But the limitations here are the technological innovations that enable elicitation process are slow and time consuming. Consumers have problems in deciding and communicating their needs which also makes elicitation hard for companies. Depending on the amount of information gathered by a company, the elicitation process becomes difficult. A proper elicitation method should make it easy for the consumer to make a choice and also for the company to gather information, usually product configurators help achieve this. (Zipkin, 2001: 81-87)

Barfod and Svensson (2002: 77-89) also talk about the use of information, they mention that in order to ensure the correctness of data businesses right now are using standards like STEP (Standard for Enablement of Product Data) and GEMS (General Methods for Specific Solutions), since this data will form the basis of an effective customized product manufacturing. Manufacturing processes in an organization should be efficient in a way that it supports high volume manufacturing at the same time be flexible and convert all the information collected in elucidation step into a physical product in the manufacturing phase. This element of mass customization is called process flexibility. Example of process flexibility enablers are computer integrated manufacturing (CIM) systems, modular product design and lean operations. The challenge with this element is again with the innovation of technologies which take a lot of time. After the manufacturing or fabrication some customer's identification data should flow along with the product since unlike mass production, products are manufactured for individual customers and hence it should reach the right person. In companies that use information system in manufacturing like the ERP systems this information processing is all taken care electronically. Levis Strauss attached bar codes with clothes after cutting them according to individual customer's preference so they could be colored in bulk but could still be sent to the exact customer. (Zipkin, 2001: 81-87).

Davis (1987) explains that mass customization can also face cultural challenges using an example of a cloth manufacturer in Italy who was able to sell only 250 customized suits in 6 months compared to the 200,000 that he sold in a mass produced way because Italians did not prefer to wait for their clothes. As Barfod and Svensson (2001: 77-89) claim "*Mass customization is not a goal but a never ending process of adaptation*".

## 3.2. PRODUCT CONFIGURATORS AND CONFIGURABLE PRODUCTS

Product configurator is a software tool that helps in product specification by structuring the ways to combine predefined properties (Anders et al. 2012: 471). Product configurator also acts as an enabler of mass customization mainly in the data collection and interpretation phase. It enables the manufacturer to react quickly to customer's needs and provide a sales order or quotation to it. It reduces the distance between the sales and the R&D team through its ability to show the sales person what properties can be added to a product and how much time is needed for manufacturing the product with those chosen properties. Since product configurators also give the final price of the product a sales person can promise the delivery date and cost of the product to the customer no matter how complex the product is. In the end this reduces the lead time in manufacturing complex configurable products by eliminating the time taken for communication between the sales person and other relevant teams.

### 3.2.1. CONFIGURABLE PRODUCTS AND CONFIGURATION MODEL

According to Tiihonen and Soininen (1997) unlike mass produced and craft manufactured products a configurable product and the configuration model is designed during the product development process and is used over and over again in the sales and distribution process. The authors mention that a mass produced product is designed as a single product instance which is manufactured again and again and a craft manufactured/ full customized product is designed as a single instance which is manufactured only once but the parts of it could be used in other products. The same article describes that during the configuration process a configurable model could be combined into 100s or even 1000s of combinations but a complete configurable model also contains the constraints to limit the number of these combinations. In the sales configuration process a configurable model helps in viewing all the product options and in the engineering configuration it produces the technical details for manufacturing the product. The configurable model could be completely configurable, where all the variants that could be configured from that model is already designed and their manufacturing feasibility is tested, in other case the model could be partially configurable where some features of the product is left for the customer to define (Forza and Salvador, 2007).

Tiihonen and Soininen (1997) argue that although configurable product knowledge could be reused in the design process, the configurable model might become problematic to manage if the rate of change of customer need is high, because as the customer need changes a configurable product evolves adding and removing component modules to it So, simpler the model, easier it is to manufacture it and also convey the possible characteristic combinations of the model to the customer. Configurable products could be developed using modular architecture where every component in the product architecture represents a characteristic of the product used for configuration, adding or removing a characteristic will add or remove a component that could fit well with other components thus making the product model simple (Forza and Salvador, 2007). More variants could easily be added to a configurable product designed using modular architecture (Ulrich & Eppinger, 2008) still the number of choices could be kept low so that customers won't find it hard to choose a product and also the organization's manufacturing processes should allow the expansion of the product platform (Meyer & Lehnerd, 1997). As Meyer and Lehnerd (1997) has recorded the power tools manufacturer Black and Decker was able to roll out a new product every week after completely creating a product platform for all their products containing standardized and common components. A configurable model should be perfectly documented, in case customer's demand a rare configuration that does not fall under the scope of the model the additional modules could be added to the model to manufacture that rare variant but it is considered economical to not add these modules in the overall model (Tiihonen & Soininen, 1997).

In order to sell a configurable product Forza and Salvador (2008) recommend that during sales configuration phase a company clearly explains its product portfolio to the customer and make them choose a variant only from that 'product space'. After this the technical characteristics of the product should be linked to the chosen commercial characteristics of it and a feasibility assessment needs to be done. According to the authors, by following these two steps a company that offers configurable products could be more efficient and responsive to the customer.

### 3.2.2 PRODUCT CONFIGURATORS AND CONFIGURATION PROCESS

According to Helo, Kyllonen and Jiao (2007: 1302-1306) a product configurator is both a sales and production planning tool that converts customer needs into BOMs, routings and final price of the relevant product. Bourke and Kempfer (1998: 42-52) define product configurator as " *software modules with logic capabilities to create, maintain and use electronic product modules that allow complete definition of all possible product option and* *variation combinations with a minimum of data entries and maintenance".* They also argue that, in order to successfully implement mass customisation efforts should start from the product design phase by designing modular products and a configurator should be used effectively. Tiihonen and Soininen (1997) define product configurators as "*an information system that is used to configure product instances and to create and manage configuration models of products".* Configurators also support the user in the configuration task and calculate price, and delivery time, and generate documentation and layout drawing. Price, delivery time, documentation and drawing functionality of a configurator depends on the type of the configurator. (Hieskala, Tiihonen, Paloheimo and Soininen, 2007: 1-32)

A product configurator helps a sales person to face the customer with certainty as he/she has access to all the technical information related to the product through the configurator which is otherwise spread across an organization. High product variety usually creates errors in the sales configuration process, by using a product configurator variety could be limited thereby reducing errors. It backs up the sales person with technical data and avoids the need for a product development personnel's help while negotiating with customers. Hence product configurator reduces the order acquisition cost and time and also avoids the unexpected costs in production activity that may arise because of configuration errors. Since technical people do not have to support sales people when a product configurator is present, they can be utilized more in new product development and can concentrate in developing a rational product architecture which is essential for any product configurator. (Forza and Salvador, 2008: 817-836). Steger-Jensen and Svensson (2004: 83-103) talk about cost savings done by configurators, they argue that validating the information for production and engineering tasks are the major cost consumers in manufacturing a configurable product. With the help of constraints, rules and consistency checks configurator allows only valid technical data to the shop floor and save costs by avoiding manufacturing error.

Forza and Salvador (2007) define product configuration as "*all the activities from the collection of information about customer needs to the release of the product documentation necessary to produce the requested".* A configuration process identifies the customer requirements, selects the relevant components from the configuration model, does pricing, check if the configuration is complete and generates a proposal and technical specifications (Tiihonen & Soininen, 1997).

Sales and technical configuration processes combined forms the configuration process. Sales configuration process is the first step and takes a commercial point of view during which the customers answer a set of questions that define the features of the product that they want. The main objective of this process is to identify a product that perfectly matches the need from the range of products the company has to offer. The process starts with explaining the product portfolio of the company to the customer and letting him explore the portfolio through the product characteristics. In the end configuration's consistency is checked and information about what kind of product the customer needs and what the company agrees to offer is generated. This might also come with price and delivery time information. The technical configuration process takes the results of the sales configuration as inputs and generates the required technical information for producing the product for the customer. This information could be technical drawings, bill-of-materials and routing and operations list. (Forza and Salvador, 2008: 817-836, 2007)

Forza and Salvador (2002: 87-98) conducted a case study about a small and medium scale electrical transformer manufacturer and have recorded how a configurator helps in sales and technical configuration process and also mention the difficulties faced by the company while implementing the configurator. The results of the study are given as followed. They discovered that when the sales team met the customers for a sales interview they found the right product match for the customer from their company by asking them a set of questions and every question generated by the configurator depends on the answer to the previous question thus making sure that all the dependencies in the configuration model are checked and the configuration is free from inconsistencies. The configurator was flexible enough to change the answer to the previous question at any given time. In the end of the sales configuration the customer received cost and an estimated delivery time but this delivery time is not determined by MRP and hence it is not accurate rather an accurate delivery time could only be given after running MRP.  After this step the configurator made it easy if the product variant was previously manufactured by the company for a different sales order, then the BOM, diagrams and routings were just retrieved from that order. So the technical team had to work on technical configuration only if the sales order is for a new product variant thus freeing them from redundant work. This was not the case before since the technical team was involved in every technical configuration. At the end of the technical configuration the configurator gave accurate technical data which avoided errors on the shop floor there by avoiding delivery date delays. Of course some employees roles were to be changed and departments had to synchronize and work together in order to make the configurator efficient, this created a little dissatisfaction among the employees and hence there was some resistance against the implementation of the configurator.

A configuration system is a combination of the configurator and the human interactions happening with it. Usually human interactions happen while creating the commercial and the technical models in the configurator and this process is called modelling. Human interactions also happen during the configuration process. The authors also based on factors like how complex the product structure is, customer's awareness about the product, resource availability and the number configurations that need to be done the configuration system could be completely or partially automated. (Forza and Salvador, 2007)

### 3.2.3 SAP PRODUCT CONFIGURATOR

According to Haag (1998: 78-85) SAP configurators approach configuration as an optimization problem because they try to find the optimal solution for the customer's need. The configuration process in a SAP configurator has high and low level configuration stages, which is identical to the sales and technical configuration process explained by Forza and Salvador. Haag also mentions that in standard SAP based configurators high level configuration is usually interactive with a user, but the low level configuration is not, but there are some cases when it comes to very complex materials where the low level configuration also needs to be interactive.

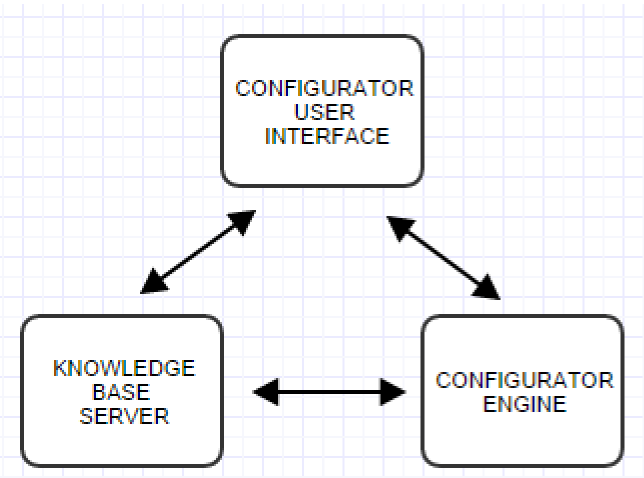



Figure 5: Key components of the SAP configurator (Haag, 1998: 78-85)

A configurable model is the main component of the configurator which contains parameters like the configurable product itself, it's characteristics which define the properties of the product (for example, color is a characteristic of the product shirt), values to be assigned to the characteristics (for example, blue and green are values for the characteristic color), BOM, dependencies and routing to manufacture the product. In SAP, the configuration model is designed in R/3 data modelling environment. A configuration process is usually fuzzy since it is affected by the mood of the person who interacts with the configurator and also by other external factors so by using the dependency directed backtracking method SAP allows the user to go back and make changes in the configuration. Whenever backward changes are done, all the dependencies assigned to the product with respect to that particular value that is being changed is also removed dynamically. With the Dynamic Database (DDB) repository the status of the configuration is dynamically updated in the repository and made available all the time. In a similar way the parameters that are necessary for the low-level configuration process is stored in a way that it could be retrieved very fast. There is a database to store every configured variant along with the accuracy of the configuration for future use. Figure 5 explains the 3 main components of the SAP configurator, the configurator user interface shows the current status of the configuration process to the user either by querying it from the configurator engine or it just displays the status sent by the configurator engine. The knowledge base server answers to all the queries about the configuration model and the configurator engine does the actual configuration and keeps updating its current state to the configurator user interface. Both the knowledge base server and the configurator engine could handle multiple queries at a time. (Haag, 1998: 78-85)

### 3.2.4. CONFIGURATOR DEVELOPMENT STRATEGIES

Haug et al. (2012) explains that in order to implement an effective configurator correct product knowledge should be maintained in it which is collected from experts in the areas of design, engineering, manufacturing and sales in a company. This process is done by knowledge engineers and is called knowledge acquisition. *"The process the knowledge engineer goes through studying the expert's behavior, uncovering the expert's underlying knowledge, and selecting and employing a tool to build a knowledge system, is called knowledge acquisition"* (Harmon & King, 1985: 82).

After acquiring knowledge the knowledge should be represented in formal ways in the next step called knowledge representation. Product Variant Matrix (PVM) diagrams and Class

Diagrams are usually used in configurator development projects for capturing and representing product information. PVM diagrams describe classes, their properties and how these classes are related to each other. It also explains the limitations in assigning the properties to the classes. The part-of section in PVM is placed on the left side and represents classes wherein the kind-of section is placed on the right and contains properties. (Haug et al. 2012: 471-481).

In theory, there are 6 main processes to create and maintain a product configurator but in reality not all these steps are followed some are skipped or merged into other steps. In the first step 'elicitation' the knowledge engineer gathers information relevant to the product from relevant experts. This received knowledge could be in the form of diagrams, sketches or formulas etc. The second phase 'translation' is when the collected information is converted into models for analysis and is optimized. Focus changes in the third step 'formalization' and created analysis models are converted into a more understandable language for configurator implementation.  In 'documentation' phase the formalized knowledge is recorded and represented in a way easily understandable for a third person. In 'implementation' phase the models are implemented as configurators using software and changes to design models are possible in this step. In case of changes in the previous step the documentation is updated again in the 'synchronization' step. (Haug et al 2012: 471-481)

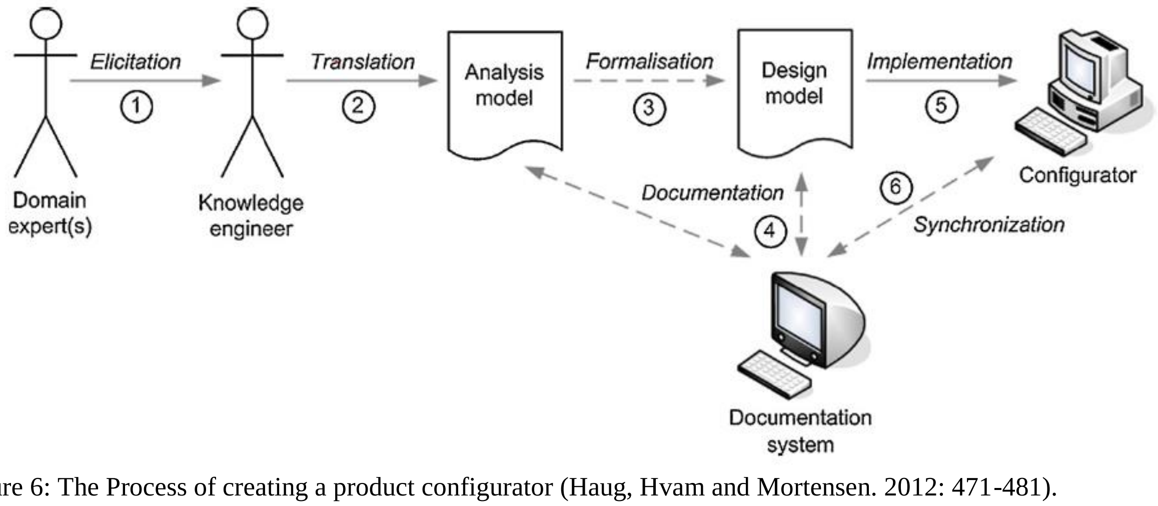



Figure 6: The Process of creating a product configurator (Haug, Hvam and Mortensen. 2012: 471-481).

Haug et al (2012: 471-481) has studied almost 50 configurator implementation projects in 15 years and have recorded the 7 strategies that were used in them. The results of his the study explains that all these strategies use a knowledge expert, a configuration software expert and a knowledge representation expert. The role of a product expert is to give the information regarding the product and the knowledge representation experts documents it, the configuration software expert converts this represented knowledge into configurator software using the necessary software skills. Figure 7 represents one of the seven strategies and is not the most commonly used one in industries. In this strategy the person who has the knowledge about the product also represents it and maps it in configurator software.

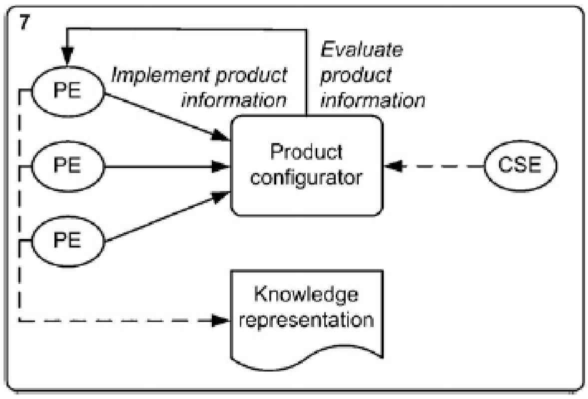



Figure 7: Configurator development strategy (Haug, Hvam and Mortensen, 2012: 471-481)

The authors mention that although this is not the most commonly used strategy it might work well if the number of people involved in the project are less.

### 3.3. ADDITIVE MANUFACTURING

One may easily think that 3-D printing is similar to rapid prototyping, although prototyping is a major application of 3-D printing there are a few differences between rapid prototyping and 3-D printing, 3-D printers are less expensive than rapid prototyping machines and also current day's 3-D printer can easily integrate with CAD software and other digital files like MRI (Berman, 2012). Petrick and Simpson (2013: 12-16) mention that although 3D printing and additive manufacturing are used interchangeably additive manufacturing means the use of 3D printing to create final products as opposed to traditional subtractive manufacturing.

Since 3D printing technology is developing faster the price of 3D printers have reduced and have gained more customers. According to Petrick and Simpson (2013: 12-16) 3D printing affects the 3 major steps in a design-build-deliver production model. The authors elaborate that it changes the nature of design by blurring the line of differentiation between design and manufacturing as the designer himself can print and produce the product and become a prosumer– producer and the consumers of their own products. Furthermore according to the authors, traditional processes of information exchange between supply chain partners and between production stages will change and product features will direct process plan, tool paths, speeds, feeds and build orientation. Because the production volume is low, procurement and distribution need not be centralized anymore and materials can be procured locally and printed in print hubs after which the end products can be shipped though small scale shipping companies like postal services.

### 3.3.1. 3-D PRINTER

3-D printing is a new technology based on additive manufacturing where products are built by adding layers of material like plastic or metal one layer on top of another, the 3-D printer works similar to a normal desktop inkjet printer except that the 3D printer uses powder or plastics or metal to create products. As Kelly (2013) mention a 3D printer prints an object for example a cube by adding thin layers of squares one on top of the other. There are several 3D printer manufacturers in the market at present and the printer that is used for this thesis is by 'MakerBot'. This printer uses plastic to create objects, the plastic is in the form of filament wound as a bundle and placed at the rear of the printer, this filament is attached to the print head, known as the extruder which heats up to melt the plastic and form desired shapes. The objects are built on a platform known as the build plate and this particular printer can build products of maximum size 225*140*150 mm. The printer is controlled by software called 'Maker ware' with which 3D models are viewed and initial adjustments are made before starting the print. This software converts 3D models to tool path which is a program/code that determines the movement of the extruder this tool path varies according to different models.

### 3.3.2. EVOLUTION OF 3-D PRINTING

Charles Gull applied for a US patent for a device called 'Apparatus for Production of 3 Dimensional Objects using Stereo Lithography' in 1984 and was granted the patent in 1986. Stereo lithography is a technique of solidifying a liquid polymer that is sensitive to UV light using LASER. Additive manufacturing started emerging in 1987 and was commercially sold to the world as Sterolithography Apparatus (SLA). The first apparatus was SLA-1 then followed by SLA- 250 and Viper SLA. These apparatus were sold by the company named 3D systems. (Wohlers and gornet, 2012: 1-26)

Initially 3D printing was used for developing prototypes by people who mainly work with 3D product designing. They preferred this technology because it was easy to create prototypes that were identical to the final product. The cost of creating a prototype was much lesser in this method, in fact when it comes to 3D printing the major cost would be investment of time during the design phase. Due to this advantage several prototypes could be made until the expected perfection is reached, which makes the process tolerant to mistakes to some extent. The prototypes could be made in-house minimizing the chances of piracy. Later the technology was used for 'direct digital manufacturing' or rapid tooling to create finished goods. The application of this phase involves larger production runs which manufactured products that were used in live market testing. The third and final phase is yet to occur in which a 3-D printer will be owned by people like how they own desktop laser printers. In this stage people will use 3-D printers to make replacement parts for home usage, for example a shower curtain holder, chess pieces etc. (Berman, 2012: 155-162)

### 3.3.3 3-D PRINTING COMPARED TO OTHER MANUFACTURING THECHNOLOGIES

According to Berman (2012) 3-D printing like Mass customization can help firms make custom made products in small lot sizes at an economical cost. Factors like the technologies used for manufacturing, how integrated the logistic processes are in the supply chain, the raw materials used and how complex of structure could be manufactured are the key differences between 3D printing and mass customisation. When comparing 3-D printing with other subtractive manufacturing technologies Berman (2012) states that:

- In injection molding method the molds used are very expensive and hence a minimum number of products need to be manufactured for every new mold bought. Compared to this 3-D printing has almost no fixed cost and can be used for small production runs.
- Compared to subtractive manufacturing technologies 3-D printing has less waste of raw material. 95% to 98% of the raw material could be recycled in 3-D printing.
- Unlike traditional manufacturing 3-D printing requires almost no set-up time.

With the current level of development 3D printing still has software and hardware compatibility issues, also additive manufacturing usually needs post processing and parts built in the same 3D printer will have variations (Petrick and Simpson, 2013: 12-16).

### 3.3.4 POTENTIALS OF 3D PRINTING

Businesses have started to grow around 3D printing technology in recent years. One noticeable business is the printing hub where any customer can upload their 3D model to the website, select the printing location, get it printed and collect it from the location or get it shipped to their address.

Today 3D printing businesses have started to print action figures from games and movies using computer screenshots only also 3D models could be uploaded to online web stores where anyone could order that model to be printed and shipped to them in that case the web store pays a percentage of that amount to the person who uploaded the model (Thilmany, 2009: 36-40). Prosthetics industry has started to make artificial limbs for the physically challenged using this technology. This will mature to a stage that any person who needs an artificial external body part could print it themselves if they have the proper design and dimensions for it. A startup named Bespoke in USA is making this prosthetics more beautiful and appealing by analyzing the body shape of the user and finding a matching shape to the prosthetic device and also make some creative decorations and patterns on it based on the users need, all these are done using 3D printing (Mertz, 2013: 15-21). Mertz also reports that researchers from Harvard along with the University of Illinois at Urbana-Champaign have created 3-D printable electrode inks which are now tested to make rechargeable batteries the size of grain of sand, this technology could be very useful in the field of medicine in the future. Experiments have been done in the food industry to print food using 3D printers. As Tech Buzz (2014) reports ultra sound pictures of unborn fetuses are converted into three dimensional items after some post processing is done to the picture. Banks (2013: 22-26) state that although 3D printing has wide applications in the area of medicine the growth of this technology in this field is slow and still has a long way to go, hence applications like tissue implants with 3D printing cannot be expected in the near future but implants for spine, hip and dental implants are currently in use. Fischer (2013) reports that in the area of tissue culture and molecular biology 3D printing has helped a startup named Organovo in California to print liver cells, although these cells die immediately due to the lack of oxygen and other life supporting fluids further research will solve the problem. He also mentions 3D printing gives enough flexibility to the engineers to place the cells exactly where they want to place it and although these tissues are not tested on human beings they are mainly used for pharmaceutical testing.

Hod Lipson mentions in his interview with IEE PULSE that since 3D printing technology is open sourced the experiments and developments around this technology is rapid as a result the technology has reached more consumers because of the reduction in cost and consumers are using printers to make final products not just prototypes. His research team is working to include electronics also in 3D printing as a result for example not only body parts of a robot could be printed but also the electronics that makes it work could be printed along with it. (Mertz, 2013: 12-14)

In future 3D printers will be owned by people in the same way how they own 2D printers now. Products will be downloaded instead of being purchased from online stores and people will make their own products rather than asking a company to make it customized for them.

## 3.4.SAP VARIANT CONFIGURATION

SAP variant configuration is used to create a configuration model and a configurator for a product that has a complex structure. For interactive configuration of a product the minimum requirements that we need are a product, characteristics with assignable values, a variant class and a configuration profile. Variant class takes care of combining characteristics and assigning it to the product, and the configuration profile has basic settings for interactive configuration (Blumhör, Munch & Ukalovic, 2012).

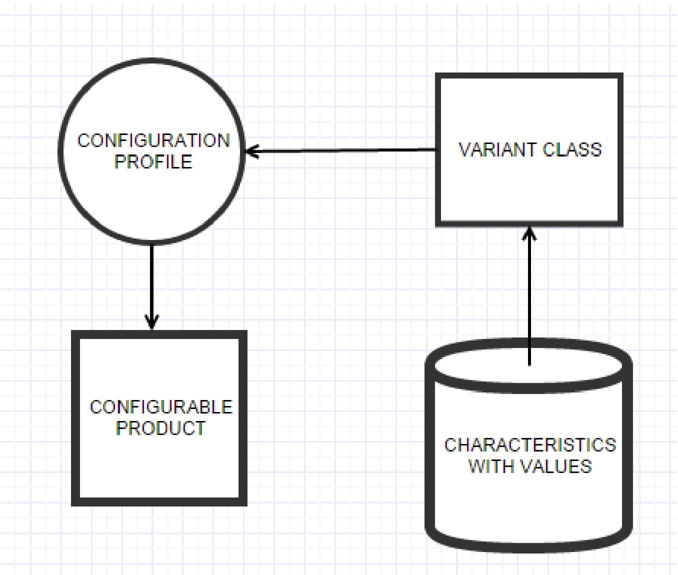



Figure 8: Basic procedure of variant configuration (Blumhör, Munch & Ukalovic. 2012: 35)

In a sales scenario when sales personnel interact with the customer to sell a configurable product or when the customer themselves try to purchase a configurable product off internet then they come in contact with the company's configurator. Organizations that run SAP ERP usually build their configurator using SAP variant configuration. In real life scenario, figure 9 translates as follows. When a person uses a configurator to configure a product they assign values to the characteristics in the sales order configuration step which are connected to the configuration profile and in turn with the actual product being configured using the variant class. Class is also a convenient method to collect all the useful characteristics and values in one place and could be used in different products wherever necessary.

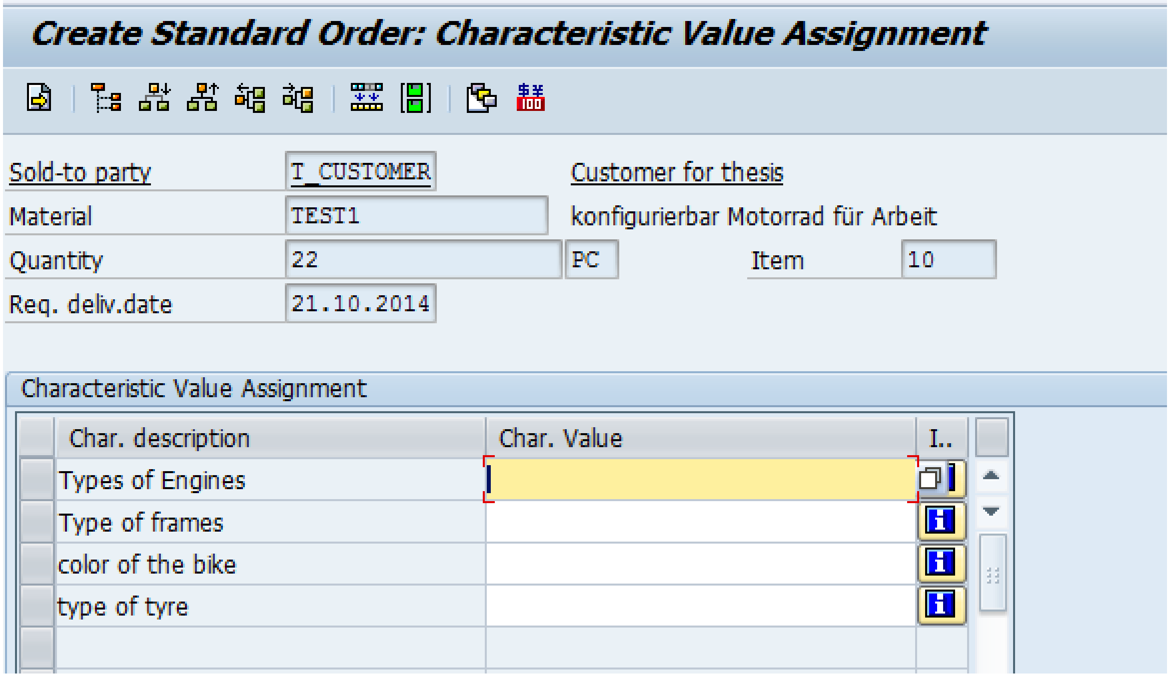


Figure 9: Value assignment screen in sales order creation phase

The configuration profile takes care of the important steps that happen after the configuration phase, generally this profile contains settings to indicate how many steps of configuration are needed and how many levels of BOM explosion are needed and what kind of configuration scenario is used. Variant configuration not only helps in creating a creating a configurable product data in SAP but also helps in maintaining the data for long term and classifying the data for easy use in the future. It also allows the flexibility of using different configuration profiles for the same product which will allow the same product to be used in different sales and production scenario.

Blumhör, Munch and Ukalovic (2012) explain that variant configuration has the following features:

1. It reduces the number of material master to be created for each variant of the configurable product there by reducing the master data in the system. It requires one configurable material, one BOM and one routing. With this many number of variants could be configured. The number of variants that could be configured could be determined using a formula which is discussed later in this section.
2. The features of a configurable material are defined using CHARACTERISTCIS.

3. All the created characteristics are collected in a class type 300 in order to assign it to a configurable material.
4. The configurable material is assigned to the created class.
5. Dependencies control the combination of values to create a variant.
6. Each configurable object contains a configuration profile this configuration profile controls the configuration process for the material in the sales order.
7. Pricing is used to fix the price of the variant depending on the characteristic values assigned.
8. Variant conditions are used to define surcharges and discounts for variants.
9. Variants that are required frequently are called material variants and could be produced without a sales order and kept in stock.

According to Blumhör, Munch and Ukalovic (2012) apart from Product configuration which remains the most frequent area of use for SAP variant configuration, VC could also be used for the following reasons:

(i) Standard Networks

Standard networks could be used as a template for creating project networks which describes a sequence of processes that repeats quite often. While creating a project network the system determines suitable standard network from the possible configurable network.

(ii) General maintenance tasks

If we are creating plant maintenance operations list the system determines a suitable maintenance task list from the available configurable tasks list. This determination happens in an interactive way.

(iii) Model service specifications

This is a combination of frequently required services. The system again determines a suitable variant from a configurable service specification which again happens in an interactive configuration task.

Product configuration is the task of defining the specifications of different variants of a configurable material and this task has the following 3 steps as follows: (Blumhör, Munch and Ukalovic, 2012)

(i) Formal description

The set of parameters or product options of the product is defined formally, and therefore it becomes a configurable product.

(ii) Definition of Parameters

Individual values for the parameters are selected based on the formal description.

(iii) Recording the specification: specification records the values that create individual appearances of a product.

The authors also state, the 3 steps mentioned above may also be called modeling, configuring and saving respectively.

The number of variants a product can have is determined by the number of characteristics (m) that the product has and the number of allowed attributes (n) that could be assigned to the characteristics using the following formula. (Blumhör, Munch & Ukalovic, 2012)

Number of variants (k) = $n^m$

Blumhör, Munch and Ukalovic (2012) also say that as the number of characteristics of the product increases the number of possible configurations will increase exponentially. This may lead to a huge number of configurations that may become highly impossible to manage. So the configuration rules and restrictions come into picture here to reduce the number of combinations a person is able to make from the available characteristics and values.

## 3.5. HOW TO CREATE A PRODUCT MODEL FOR SAP VC

### 3.5.1. DEFINING A MATERIAL AS CONFIGURABLE

According to SAP help portal, a configurable material could be configured in many ways into many different variants even though it is represented by only one configurable material. To create any configurable material the pre-requisite is to mark the material as configurable while creating the master data which could be done by two ways:

(i) By selecting the material type *KMAT* which is a standard material type in SAP system to create configurable materials.

(ii) Other material types could also be made as configurable materials by selecting the configurable material indicator in the basic data of the material master record.

Item category group and item category number are two other important aspects to be considered while creating material master data. Item category is an important parameter in sales order and sales process. It is used for pricing the material, creating bills, producing delivery information etc. Item category for a material is determined by the item category group of the material and the type of sales order that being processed (SAP Community network wiki).

| | | | | |
|---|---|---|---|---|
| **DETERMINATION RULE** | | | | |
| **ITEM CATEGORY** | = SALES DOCUMENT TYPE | + ITEM CATEGORY GROUP *FROM MATERIAL MASTER* | + USAGE | + HIGHER LEVEL ITEM CATEGORY FROM PRECEEDING LINE |
| **EXAMPLE** | | | | |
| **SALES DOCUMENT TYPE** | **ITEM CATEGORY GROUP** | **USAGE** | **HIGHER LEVEL ITEM Category** | **DEFAULT ITEM CATEGORY** |
| OR | NORM | | TAN | TANN |
| OR | Configuration | | | TAM |
| OR | NORM | FREE | TAN | TANN |

Figure 10: Formula for determining item category group (SAP community network)

Code TAN indicates that it is a standard order item which includes pricing, scheduling line and the item is relevant for billing. TANN indicates free of charge item which is not relevant for billing, so no pricing is involved which means that the item against this item category will not be included in the final price, usually this will be the case when the item is a part of the BOM whose header item is included in the pricing.

### 3.5.2. BILL OF MATERIALS IN VARIANT CONFIGURATION

A Bill of Materials (BOM) is a technical document that contains assemblies and components along with their quantity information required to manufacture a product. The different types of BOMs are material BOMs, Order BOMs, WBS (Work Break Down structure) BOMs, Sales and Distribution BOMs, Production BOMs, Engineering/Design BOM and a few others. A Bill of Material is mainly differentiated by the header material i.e. if it is a material BOM or a document structure etc. The header material for a BOM could be a material, a document, equipment or a functional location. Order BOM and project BOMs could also serve as header material. Order and project BOMs refer to a material master similar to material BOM but it also contains an additional specification or an item of a sales order or a project. (SAP Help portal)

TECHNICAL TYPES OF MATERIAL BOMs

Blumhör, Munch and Ukalovic (2012) classify BOMs into the following 3 different types:

*(i)* *Simple BOM:*
Exactly one BOM is used for one configurable material. It is used in variant configuration standard.

*(ii)* *Variant BOM:*
This type of BOM is used if the materials are similar but still different. This is used in case the components in the BOM hardly differ.

*(iii)* *Multiple BOM:*
This type of BOM is used if the same material exists in different production scenarios. Accordingly in this type of BOM, same material has several BOMs.

SUPER BOM FOR A CONFIGURABLE MATERIAL:

According to Blumhör, Munch and Ukalovic (2012) a configurable material requires BOM information in several places like costing, production, MRP etc. it also requires BOM for product costing and implementing multi-level configuration. A configurable/super BOM is used for his purpose. A super BOM could be a simple or a dynamic BOM or a multiple BOM according to the technical classification of BOMs. In a super BOM structure all materials above a configurable assembly is configurable.

A super BOM as a simple BOM means that it is a BOM number that contains exactly one BOM for one material. Whereas, a super BOM in the form of a variant/multiple BOM means that it is a BOM number under which one BOM is stored for each material master of several similar material masters. In a super BOM components can be assigned directly as material or document items or indirectly via class items. Class items could be assigned to super BOMs only if the header material is marked as configurable material in the master data. (Blumhör, Munch & Ukalovic, 2012) Using class items in BOMs is explained in the next section.

According to Blumhör, Munch and Ukalovic (2012) a super BOM needs also to be exploded if there are configurable assemblies in the BOM. This explosion can be implemented in the following 2 ways.

*Dynamic BOM:*

This type of BOM explosion can be used when all the possible combination of variant materials could be made from the super BOM. If the variability of the configurable product is not higher in sales and distribution then dynamic BOM explosion is used. In order to use this type of BOM explosion the master data we need are the super BOM and the object dependencies. In case, if the BOM information is required by planned order or production order or sales order the information is made available only temporarily using the object dependencies and configuration. The system can only copy the corresponding component list from here but it does not generate explicit order BOM.

*Order BOM:*

Order BOMs are material BOMs that are specific for an item in the SD document. This SD document is a sales order in most cases. Order BOM helps in implementing order specific product development. If the variability for the configurable product needs to be more that the variant model, mainly in the super BOM then order BOMs are used.

USING CLASSES IN BOM:

In a BOM for a configurable material, CLASS could only be used to group either materials or documents. The class type of the class defines if materials or documents are classified in the class. Either class type 200 or 300 could be used as class types while creating class. The class has characteristics and different values assigned to the objects (materials or documents) classified under the class. When the class is selected any one item which is classified under the class is chosen to be displayed in the BOM. While creating a class the ‘allowed in BOM’ indicator should be selected so that the class could be used in the BOM, the picture below indicates how class items are enabled to be used in BOMs. (SAP Community network wiki)

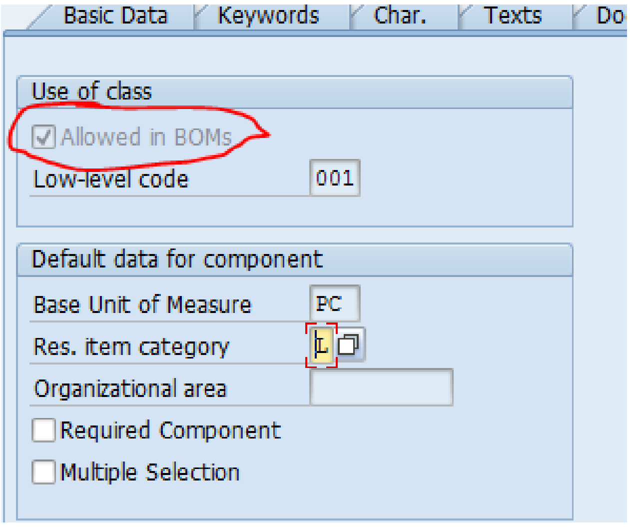



Figure 11: Creating class items

As an example to demonstrate the use of class items in BOM let us consider the picture given below, the BOM is for a product name BIKE. In the first box on the top the column 'type' indicates the type of BOM item, if the type is K it is a class item and if it is L it is a stock item.

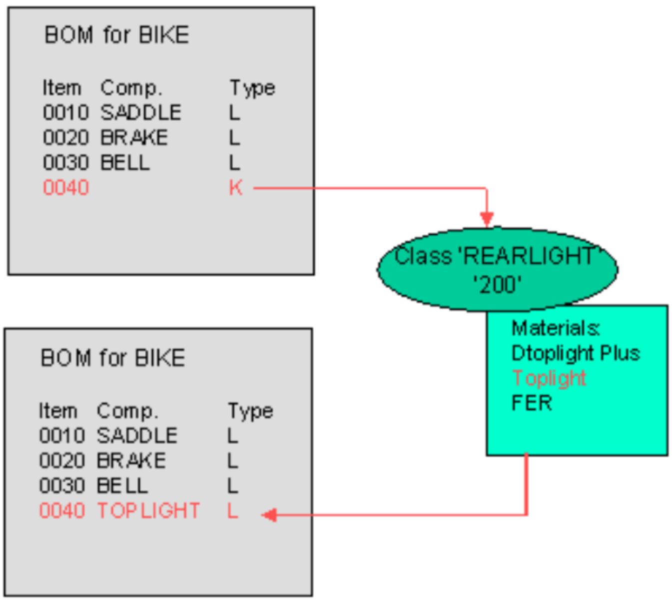



Figure 12: Class item in BOM (SAP LO-VC,2000: 25)

So the BOM CLASS item REARLIGHT is selected in the BOM which has 3 characteristic values under it namely Dtoplight Plus, Toplight and FER. So, there are already 3 items classified under this class with these 3 different values assigned. So according to the value we want we can choose the item from the class. This method of using class items in BOM avoids the complication of allocating selection conditions for each configuration.

ITEM CATEGORY IN BOM:

According to Blumhör, Munch and Ukalovic (2012) each item in a BOM requires an item category and in super BOMs all item categories can be used for material BOMs. The following are some of the item categories as described by the authors:

*L Stock Item:*

These items are used for direct assignment of material components. As the name says these items are procured from stock.

*N Non Stock item:*

These items are also used for direct assignment of material components. They are not procured from stock. They are directly procured through orders. Only materials with KMAT material type can be included in this item category as BOM items.

*R Variable size items:*

These types of materials could also be used for direct assignment of material components. These types of materials are particularly interesting in variant configuration because item sizes of this kind of items could be changed using object dependencies with reference characteristics.

*D Document item:*

If object dependencies are supposed to be used to control the selection in BOM then document items are assigned to BOM.

*K Class item:*

Class items are explained in section 3.6.2 under the topic *USING CLASSES IN BOM.*

### 3.5.3. SUPER TAKS LIST/ROUTING FOR CONFIGURABLE MATERIAL

Similar to super BOM a super task list or super routing contains operations that needs to be performed, time taken by the operation and the tools needed during the operation to manufacture all the variants of the configurable material. In-house production the configurable material requires information from the production process and also for activities like scheduling, production planning, costing etc. A super task list is used for this purpose and object dependencies are used to explode the routing according to the configuration. A super task list contains all the possible operations and operating facilities for any possible configurations. These operations and operating facilities could only be added directly to the super task list and cannot be added directly using classes. (Blumhör, Munch and Ukalovic, 2012)

ROUTING EXPLOSION

Blumhör, Munch and Ukalovic (2012) say that similar to BOM explosion routing explosions can also be implemented in the following 2 ways:

*Dynamic sequence:*

If the routing information is required by planned order or production order or sales order then this information can be made available from the super task list by means of object dependencies according to the configuration and this information can be made available only temporarily.

*Order routings:*

If a customer specific routing needs to be created for a configuration, then order routing method can be used. This can be done by using a simulative exploded routing as the template. This type of routing explosion doesn't require any specific setting.

STRUCTURE OF ROUTING:

According to Blumöhr, Munch and Ukalovic (2012) in standard form routing contains header, sequences, operations, sub-operations and assignment to operations and sub-operations. The contents of routing are explained below according to the authors:

(i) *Header* is the highest-level structure element of the routing. Usually, the configurable material is assigned to the header. Object dependencies cannot be assigned to the header and task list selection cannot be controlled using object dependencies.

*(ii)* Operations below the header material are collected under the *sequences*. There is always a *standard sequence* to which object dependencies cannot be assigned. If operations need to be processed in parallel then they are collected in *parallel sequences.* If we need alternate operations to the standard operations then it could be collected in *alternative sequences*. Object dependencies could be assigned to parallel

and alternative sequences to control their selection and assignment in the routing explosion.

*(iii)* *Operations* are listed under sequences and object dependencies are used for the selection of operations.

*(iv)* Tools and other operating facilities can be assigned as *production resources and tools* to operations. These are in the form of super lists from which we can select the required tools and resources using object dependencies according to the configuration. Additionally, objects like work centers, components, inspection characteristics and trigger points could be assigned to operations but their assignment cannot be controlled via object dependencies.

### 3.5.4. CONFIGURATION PROFILE AND SCENARIOS

#### CONFIGURATION PROFILE – INTRODUCTION

According to Blumöhr, Munch and Ukalovic (2012) configuration profile is necessary to implement a configuration because it controls the essential control settings for the configuration process and object dependencies for the sales configuration. Additionally they also mention that a configuration profile is created for every material master and a name and a variant class type assigned to it but the name can be changed retroactively. In some cases multiple configuration profiles can be assigned to a configurable material. The examples are given below as described by the authors:

*(i)* *Header level:*

At the header level of a configurable material several active configuration profiles could be used and the sales and distribution team decides which profile to use for a specific order.

*(ii)* *Configurable assembly level:*

If one configurable assembly is used in various configurable products it is possible to assign different configurable profiles to this assembly and then select the appropriate one accordingly to the configurable product. In this case all the configuration profiles assigned to a configurable assembly cannot be used with the profile assigned to the configurable product. The system selects the only possible profile to be used.

The authors also say that by assigning the variant class type 300 to the configuration profile we can check if this same class type is assigned to the material master, if not we can do this assignment retroactively. If a variant class type is not assigned to a configuration profile the system locks it and the lock has to be manually released after the assignment.

CONFIGURATION PROFILE – DESCRIBED IN DETAIL

According to Blumöhr, Munch and Ukalovic (2012) assigning global object dependencies, BOM explosion levels, and the area where the BOM is used (for example if it is used in SD or in production), and the user interfaces of the configuration screen are a few functions that could be controlled using configuration profile. The authors also explain that while creating the configuration profile the 2 main screens/tabs in which we have to maintain values are the 'BASIC DATA' and the 'CONFIGN INITIAL SCREEN' which is further sub-divided into 'CONFIGURATION PARAMETERS' and the 'USER INTERFACE' tabs. The tabs are explained by the authors as follows:

*Basic data tab:*

Along with the options for configuring in the initial screen this tab provides options like assigning organizational areas, object dependencies and selecting start logo. The organizational areas field is a tool that belongs to the classification system. This field also enables it to filter characteristics within classes, using this option we can enable the value assignment interface to not display all the characteristics of the variant classes rather we can activate organizational areas and then assign characteristics to these activated organizational areas. We can select one or more organizational areas which enable us to select the characteristics that the value assignment interface is supposed to display for the particular configuration profile. It is also possible to have an authorization object for organizational areas.

If the start logo check box is checked the system will check during the start of every configuration if a document is assigned directly to the variant class and not via the document link and display the result as the start information.

*Configuration Parameter tab:*

The configuration parameters tab has 2 settings namely 'process' and 'BOM explosion'. These two settings mainly define the configuration scenario and the level of explosion of the BOM. The same BOM application defined here will be used in the configuration simulation and in all other applications of the supply chain where no other specific BOM application is found. The filter is active in high-level application and helps us to filter and retrieve BOM objects like material, class, document and text.

Under order functions the component availability check box enables us to run an availability check only at the component level in the configuration simulation. But, this check does not have an effect on the availability check in the SD documents such as sales order. It is only simulative and does not affect the requirement and stock situation. If we choose multi-level BOM explosion the system displays another option ‘only configurable assemblies’ under ‘level of detail’ which will enable us to restrict the BOM explosion to only configurable assemblies. But, since this creates performance issues it is better left unchecked.

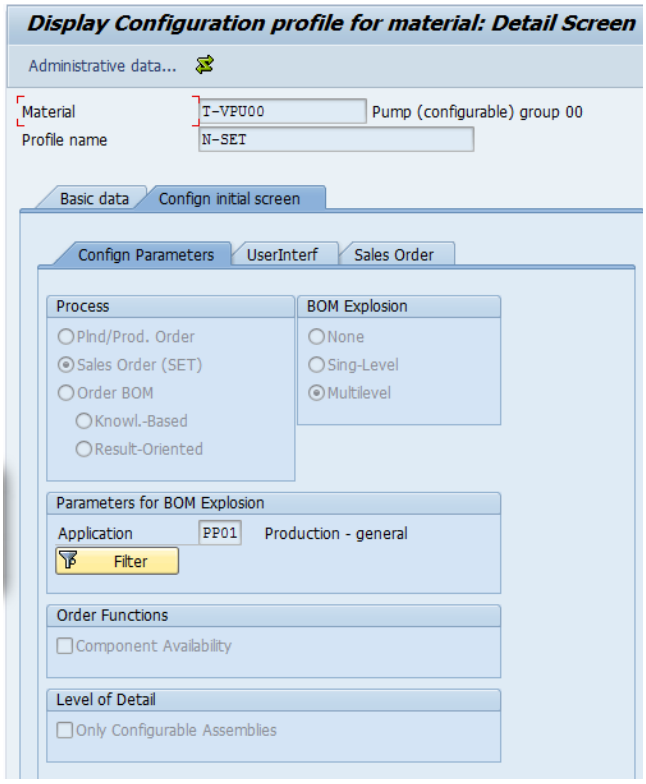


Figure 13: Configuration parameters tab in configuration profile

*User interface tab:*

This tab has the ‘Interface Design’ option and ‘Settings’ button. The system displays more options if any kind of BOM explosion is chosen in the previous tab. This transaction is mainly to configure the user interface screen used during the configuration process. The user interface needs to be named first and it is possible to use one user interface to multiple configuration profiles but then all the configuration profiles needs to belong to the same variant class. In other words, multiple configuration profiles used for the same header material could use the same user interface. With this tab we can manage settings for languages, pricing, presentation of allowed characteristic values, scope of the characteristics, default values, configuration etc.

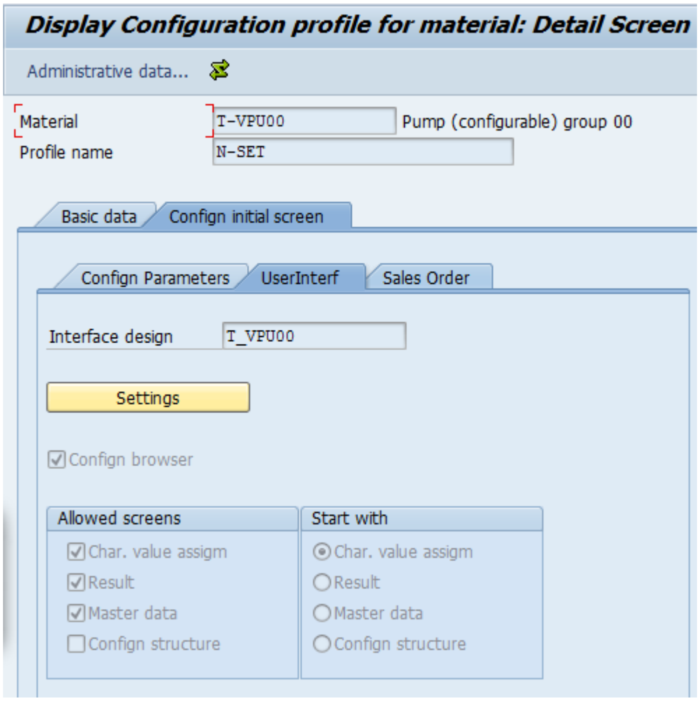



Figure14: User interface tab in configuration profile

## CONFIGURATION SCENARIOS

There are 4 types of configuration scenarios in SAP variant configuration. A configuration scenario definition is a very important part of configuration profile and helps us answer the following questions.

"*1. Does the SD document require a BOM explosion?*

*2. How many levels are supposed to be used for the configuration?*

*3. Does the BOM explosion needs to be adapted manually? If so, where is the manual adaption supposed to be implemented?"* (Blumöhr, Munch & Ukalovic, 2012).

In variant configuration there are 4 types of configuration scenarios namely planned/production order with BOM explosion scenario, planned/production order without BOM explosion scenario, order BOM scenario and sales order (SET) scenario. This thesis uses the planned/production order with BOM explosion scenario in the empirical part hence I limit the explanation only to that scenario in this part. This scenario assumes that the variant model contains all the possible characteristics, values, BOM and routing for all the variants that could possibly be configured from this variant model. The BOM is exploded in sales and distribution after the configuration and the configuration could be both single-level and multi-level. The BOM explosion cannot be adapted manually in this scenario (Blumhör, Munch and Ukalovic, 2012).

### 3.5.5. OBJECT DEPENDENCIES

According to Blumhör, Munch and Ukalovic (2012) object dependencies play a role in both high level and low level configurations. In high level configurations the object dependencies help in limiting the characteristics and values that are not relevant to the particular configuration, assign default characteristics and values to the product at the beginning of the configuration, and to restrict value assignment combinations that are not combinable. By doing so, the object dependencies make a configuration complete and consistent in the high-level i.e. the sales order configuration. After the sales order configuration is complete the object dependencies select the appropriate BOM items and routing operations according to the configuration which is called the low level configuration.  Four types of object dependencies are available which the authors describe as follows:

*(i)* *Preconditions:*

Without a precondition any value could be assigned to a characteristic irrespective of other assigned values to the same or even other characteristics. Preconditions can make available some values or even complete characteristics only based on certain conditions. Preconditions could be both assigned to the characteristic and to the characteristic value. Based on the character a precondition is a semi-declarative object dependency.

*(ii)* *Selection Condition:*

Selection conditions are used in low-level configuration. They explode the BOM and routing based on the configuration and is mainly applied to BOM item selection, assigning sequences in the routing, selecting operations in the routing and selecting tools and production resources in the routing. If a selections condition is not assigned to a BOM item and routing it is assigned to the product by default after the high-level configuration and these items that are assigned by default are called non-variable parts and the ones to which a selection condition is assigned are called variant parts. Based on the character selection conditions are semi-declarative object dependencies.

*(iii)* *Procedures:*

Procedures are used both in the value assignment interface to assign values to the characteristics and also for elements like BOM items, assigning sequences to the routing, assigning operations in the routing and assigning production resources and tools to the routing. Multiple procedures can be assigned to an object and could be made available after the start of the configuration. A procedure could overwrite a value even if is overwritten by itself. In BOM and routing, procedures could be used to make changes like increasing or decreasing the component number or increasing or decreasing the setup time. Dependencies must be taken into consideration while using procedures, since the procedure assigns values to BOM and routing irrespective of whatever dependency is in place. Procedures can assign values permanently to objects which could be only overwritten by another procedure and not by any other user or object dependency. It can also assign values dynamically for example if the default value for a particular characteristic depends on the value assigned to another characteristic then procedures act dynamically. Dynamic value assignment via procedures must be specifically indicated because the default is always fixed value assignment. In the value assignment interface or sales order configuration procedures can either be assigned to the configuration profile or to the characteristics and values, but assigning the procedure to the configuration profile is more powerful. Based on the character procedures are procedural object dependency.

*(iv)* *Constraints:*

Constraints are a mix of both preconditions and procedures. They can both check and assign values. They are used only in the value assignment interface and are assigned to the configuration profile. Based on the character constraints are declarative object dependencies.

Object dependencies are broadly classified as local and global object dependencies. Local object dependency has numerical names like 1234 and global ones can have character names. Global object dependencies could be used multiple times at necessary places, this increases the performance and simplifies the maintenance of it in case of an error, hence global object dependency is advantageous to use compared to local ones. (Blumhör et al. 2012)

### 3.6. ORDER FULFILLMENT

A configurator eliminates the back and forth information exchange between the customer and the manufacturer and avoids the lead time during configuration by at least 10 folds. Without a configurator the configuration should be done also with the help of the design or technical team (Tiihonen and Soininen, 1997). According to figure 7 the customer configures the product using two configuration models one for sales and another for engineering configuration but in reality it is possible to combine both the models together. After which the components are purchased or manufactured then assembled according to the technical operations produced as an output of the configuration which gives us the final product instance that the customer ordered.

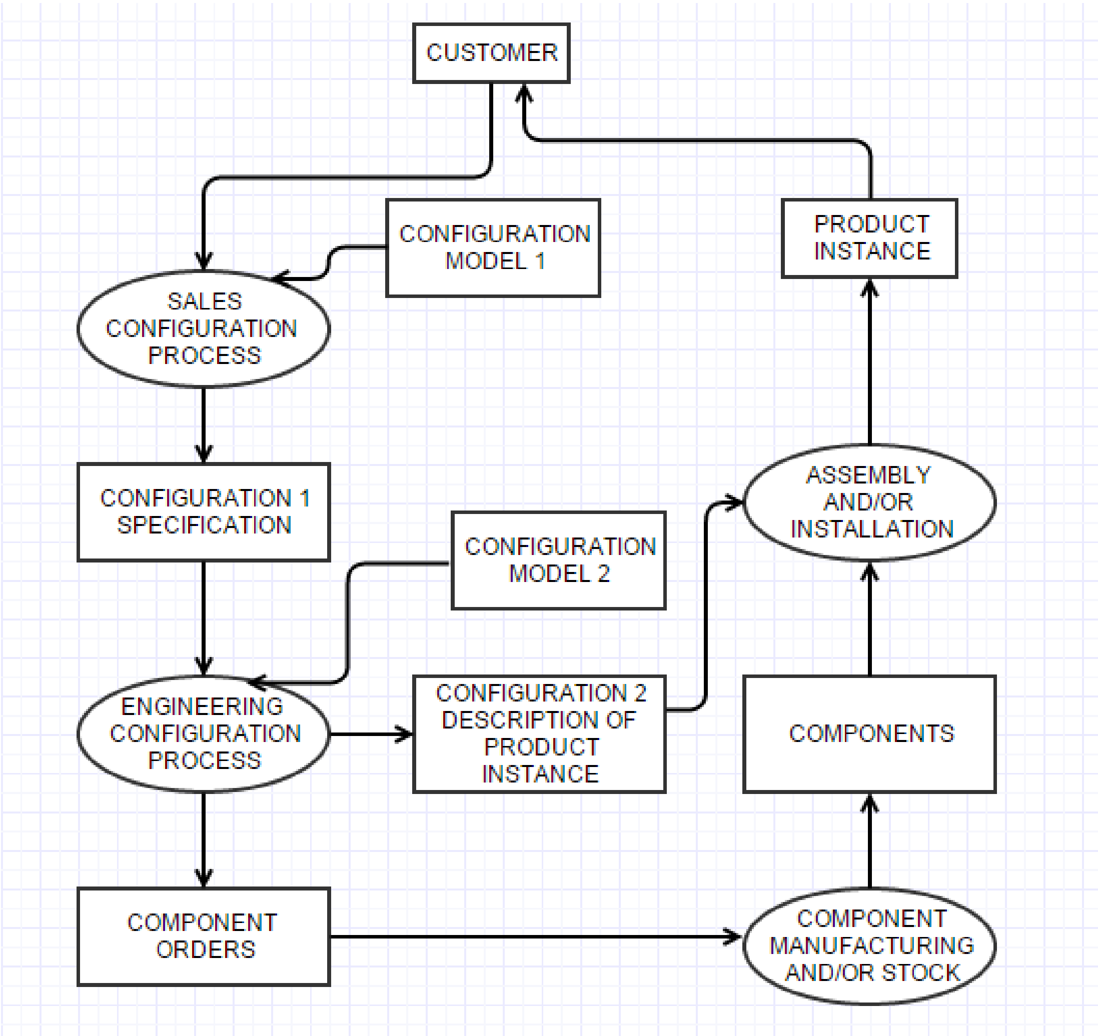



Figure 15: Sales Delivery process of a configurable product (Tiihonen and Soininen, 1997: 6)

When using a product configurator in SAP ERP the sales delivery process starts with the creation of sales order. In transaction VA01 a sales order of type 'OR – Standard Order' is created for the configurable motorcycle. Once data like the material and the required quantity of it along with the name of the customer is entered in this screen the screen automatically redirects to the configuration screen where the customer/sales person configures the motorcycle according to the customer requirements.

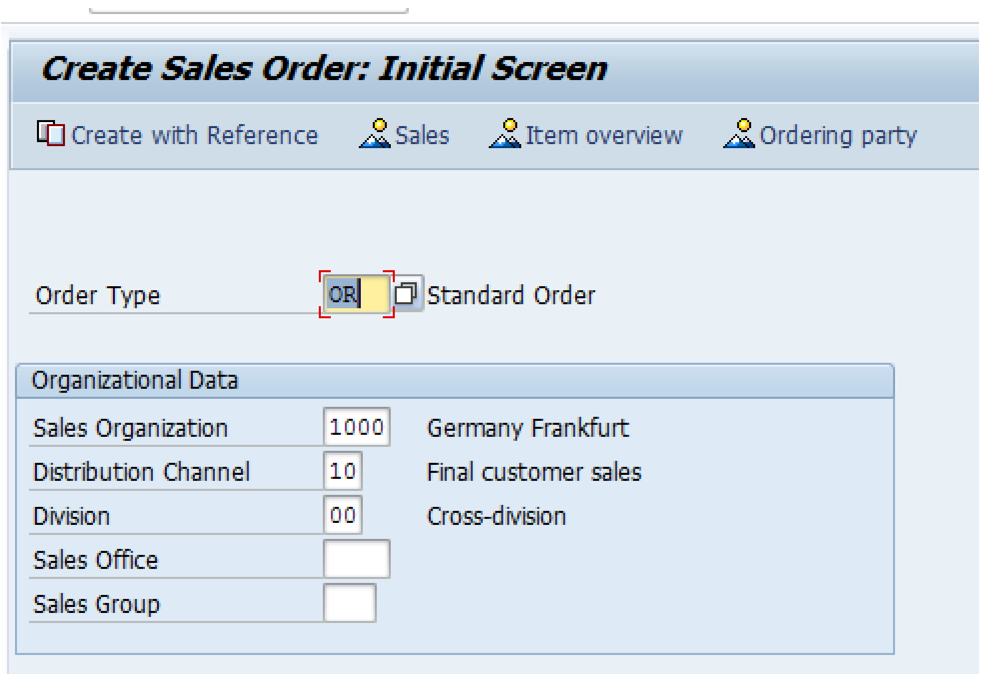



Figure 16: Sales order creation with transaction VA01

The configuration screen doesn’t allow saving the sales order before the all the characteristics are assigned with a consistent value.

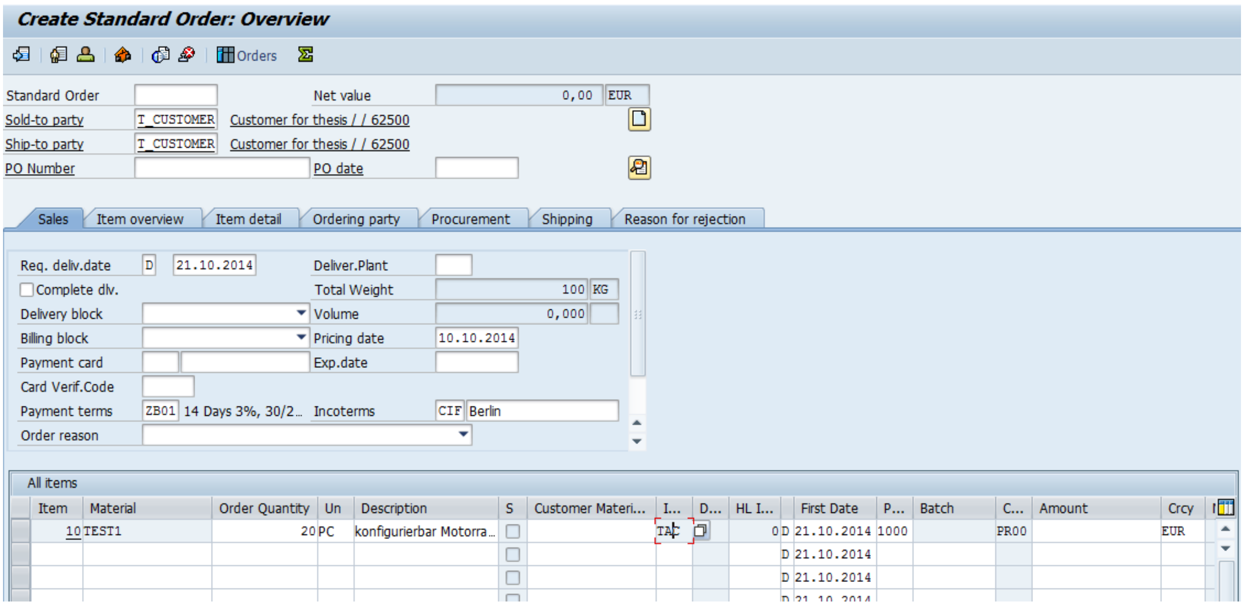



Figure 17: Entering material and quantity information in sales order

Once when the configuration is done by pressing enter key on the keyboard the system will take the user back to the sales order screen where material availability could be checked if necessary and then the sales order could be saved.

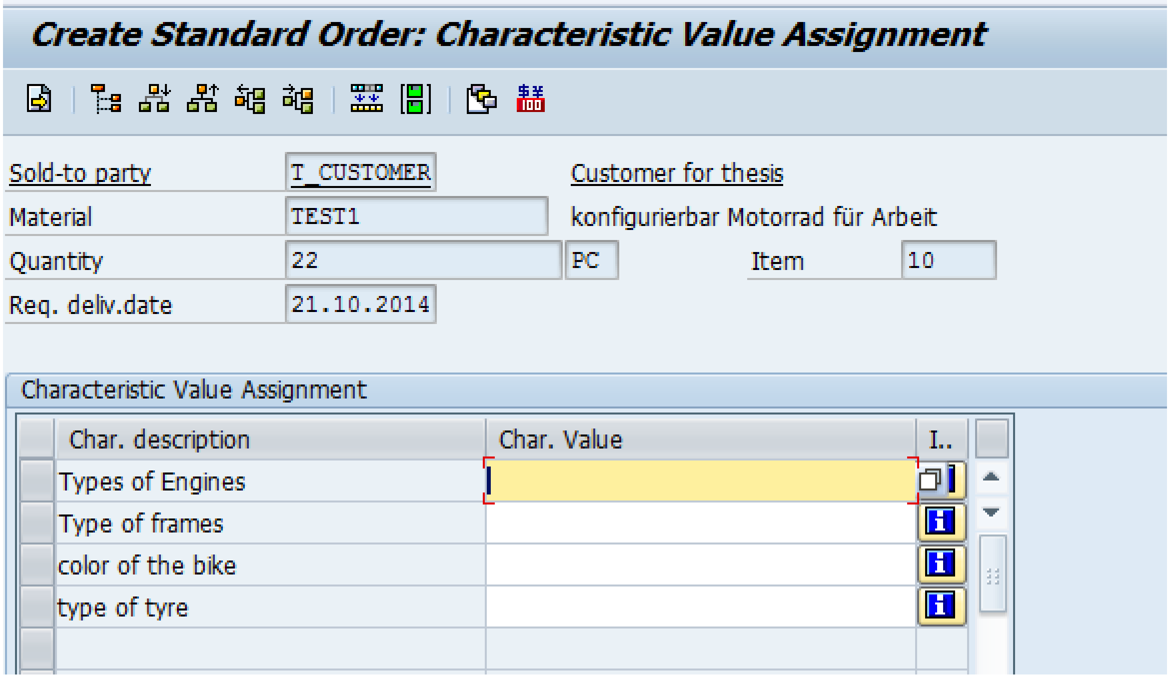


Figure 18: Configuring the product in sales order

# 4. EMPIRICAL

Aligning with the main objective of the thesis the empirical part aims at simulating a mass customization manufacturing with make-to-order strategy. The empirical part is divided into sub parts like modelling the configurator in SAP, designing and printing the components of the final product in a rapid prototype printer and designing the process for the simulation. The rapid prototype printers commonly known as 3D printers present in research center 'Technobothnia' inside University of Vaasa premises are used in the thesis. Remaining of this part will contain detailed explanation of all the steps involved in configuring a product configurator in SAP along with the pictures of the 3D printed components and the 3D printer used in the process. The part 4.3 Simulating Mass Customization contains step wise procedure to explain how the configurator and the rapid prototype printer are used together in order to simulate mass customization manufacturing.

## 4.1. CONFIGURATOR DEVELOPMENT

In order to develop the configurator, the product structure with all its properties and inter-dependencies were decided. A motorcycle was decided as the product with its components defining the properties of it. A product variant matrix (PVM) diagram was drawn along with the complete structure of the configuration model in order to decide features that need to be mapped using SAP variant configuration. The following limitations were decided for the configuration model.

(i) A two stoke engine will only have a dirt bike frame.

(ii) Only if a dirt bike frame is selected the paint red will be shown as an option.

(iii) MRF tyre will be an option only if the standard bike has a blue color.

(iv) Painting will not be a separate component but only as an operation in the routing.

(v) Colors blue and black will take 30 minutes to paint whereas red will take 60 minutes.

(vi) A four stoke engine will only be available for standard, touring, sports and cruiser bike frames

The Product Variant Matrix (PVM) diagram in figure 15 shows the overall product structure with some dependencies written in it. The characteristics Engine, Frame, Paint and Tyre are part-of the configurable product motorcycle and the values like 2 stroke engine, 4 stroke engine, etc. are a kind-of the characteristic engine, frame, paint, and tyre respectively. There are also other dependencies written in the product configurator mainly to deal with the BOM and operations. Annexure 2 is a basic diagram drawn at the very beginning of the thesis in-order to get a clear picture of the product structure that is about to be converted into a configurable model in SAP.

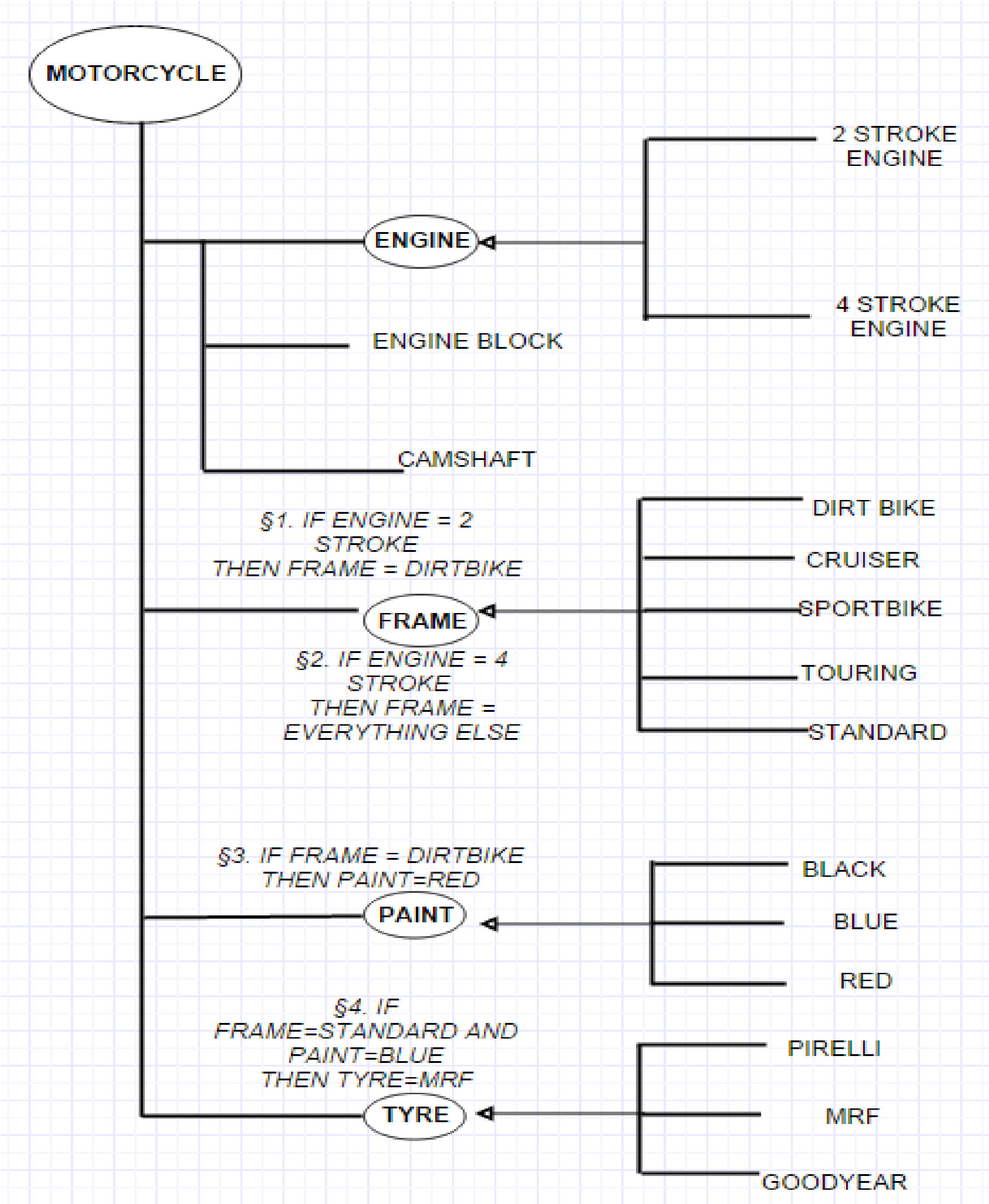



Figure 19: Product Variant Matrix Diagram (PVM) representing product information with dependencies

The following steps needs to be completed in order to create a configuration model in SAP.

1. Creating a configurable Material
2. Creating characteristics with Values

3. Collecting them in a class of class type 300
4. Creating a configuration Profile and assigning the class to it.
5. Creating super BOM
6. Creating super Routing
7. Creating dependencies

### 4.1.1. CREATING MASTER DATA

Motorcycle is the main product that comprises of 4 characteristics namely Engine, Frame, paint and tires. The following descriptions explain how the master data are created and the important points to be noted down while doing it.

*(i) Master data of header material TEST1:*

A material named TEST1 is created with the material type configurable material (KMAT). In selection of views 'Basic data 1&2, all the sales related views, MRP 1, 2, 3, &4, Work Scheduling and Costing 1&2 are selected. The product is created for Final customer sales through sales organization in Frankfurt. The material type is 'Configurable Material' under Industry sector 'Mechanical Engineering' and the plant, storage location, sales organization and distribution channel are 1000, 0001, 1000, and 10 respectively. The 'GenItemCatGroup' is 0002 in case of a configurable material. The motorcycle is transported in trucks and the loading is done manually. The type of MRP used in this case is PD. Material master and Bill of Materials are the basic data that are required to work with MRP component. When we use MRP for in-house production we also need work center and routing components. The lot size used here is lot-for-lot order quantity. With this lot size, the system will place an order with the exact shortage quantity while running MRP i.e. the system will subtract the available quantity (warehouse stock) from the required quantity and will create an order (production/purchase) only for the remaining quantity. The procurement type E denotes the material is produced internally. The strategy group used is '20 – Make-to-order-production'.

*(ii) Master data for first level BOM items:*

*ENGINES:*

Two types of engines are present in the super BOM. One is a 2-stroke engine and the other is a 4-stroke engine. The master data for the engine is taken from the material used in the SAP course conducted by the Department of Production at the University of Vaasa. The master data is used from the material [1300-110] HD ENGINE 1340 CM3/35 KW. The cost of both the engines is €511.29. The material name of the 2-stroke engine is 'Engine1' and the 4-stroke engine is 'Engine2'.

*FRAMES:*

Totally five types of frames were created for this model. Frames are semi-finished products and hence they contain an item category group 'NORM' which means these materials does not transfer any requirements or do any costing, they are only valid for display purposes in the BOM. The master data for the frame is taken from the material used in the SAP course conducted by the Department of Production at the University of Vaasa. The master data is used from the material [1300-230] HD GLAD BOY FRAME. Cost of the frames will be 100 euros each. The frames are named as follows

| | |
|---|---|
| Dirt Bike Frame | Frame1 |
| Cruiser Bike Frame | Frame2 |
| Sport Bike Frame | Frame3 |
| Touring Bike Frame | Frame4 |
| Standard Bike Frame | Frame5 |

Table 1: Names of different types of frames used in the configuration model

*TIRE:*

Tire is created as a semi-finished product. The in-house production time is 2 days and the material belongs to the division 00 – CROSSDIVISION. The different types of tires are used in this model and they are named as TIRE1, TIRE2 and TIRE3.

| TIRE | MASTER DATA NAME | COST |
|---|---|---|
| Pirelli | Tyre1 | 20€ |
| Goodyear | Tyre2 | 20€ |
| MRF | Tyre3 | 20€ |

Table 2: Names of different tires used in the configuration model

*(iii) Master data for second level BOM items:*

The second level BOM items are referred to as 'raw materials'. This model has two raw materials as the second level bill of materials namely, ENGINE BLOCK & CAMSHAFT. The master data for the raw materials are taken from the material used in the SAP course conducted by the Department of Production at the University of Vaasa.

The ENGINE BLOCK is measured in pieces and available across cross division. The planned delivery time is 2 days and a moving average price is €249.50 for both the 2 stroke and the 4 stroke variant. The CAMSHAFT is also measured in pieces and belongs to cross division. It has a moving average price of €89.95 for both the 2 stroke and 4 stroke variants.

### 4.1.2. CREATING CHARACTERISTICS WITH VALUES

There are 4 characteristics that are used to configure the motorcycle. The characteristics namely "ENGINTYPE", "FRAMETYPE", "BIKECOLOR" and "TYPE_OF_TIRE" are the characteristics that define the parts of the configurable object TEST1. All the characteristics needs to be assigned with a value during configuration and only one value could be assigned to it which is done by selecting the 'single-value' option in the basic data tab of the characteristics. The option 'restrictable' is also chosen in the basic data tab that enables us to use object dependencies in these characteristics to restrict them during the configuration process. For the colors blue and black the operation 'paint' will be selected from the super routing using object dependency and for color red the operation paint-red will be selected. These are explained in detailed in the following sections.

### 4.1.3. COLLECTING THE CHARACTERISTICS UNDER CLASS TYPE 300

All the characteristics created above are collected in a class of type 300 which is the standard class type for variants. The class is named as T_CLASS. Classes are created because it is through classes that the characteristics are assigned to the material.

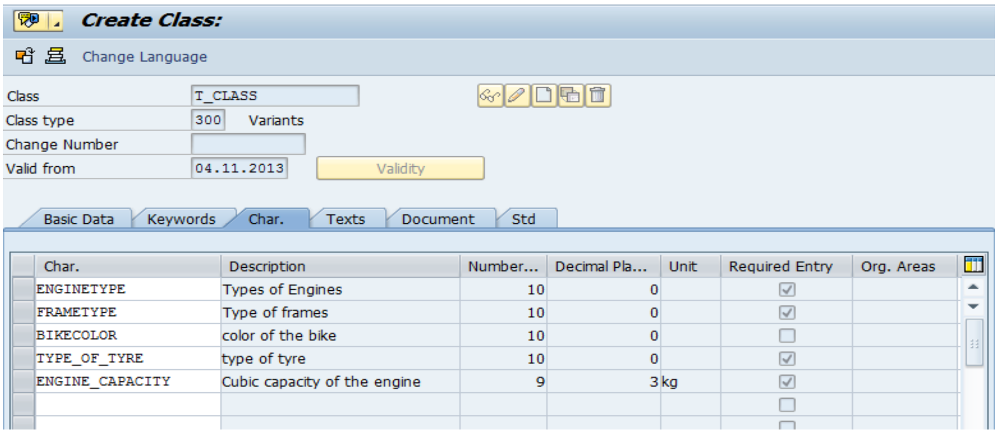


Figure 20: T_CLASS with all the characteristics under it

### 4.1.4. CREATING A CONFIGURATION PROFILE AND ASSIGNING CLASS TO IT

A configuration profile is created for the header material TEST1 and assigned to the class type 300[Variants]. The configuration scenario used here is planned/production order with BOM explosion. Since a multi-level BOM is used the BOM explosion will be 2 levels and since there are no configurable assemblies in the BOM the configuration is only single-level. The BOM explosion is used in production. Settings were also selected that could make it possible to check if components are available in stock for the product. According to the settings made the configuration will start with the characteristic value assignment interface and it would be possible to see the result screen and the also master data if needed. The configuration profile is saved with the 'released' status under the name Test1.

### 4.1.5. CREATING SUPER BOM

Dynamic BOM is used in this thesis, which means a new variant that is not part of the configurable model cannot be configured. All the material for which the master data has been created before is added to the BOM through transaction CS01 along with the quantity of the items required for creating one header item.

**06.10.2014** **Dynamic List Display**
**1**

**Material** TEST1
**Plant/Usage/Alt.** 1000 / 1 / 01
**Description** test1 bike
**Base Qty (PC )** 1,000
**Reqd Qty (PC )** 1

| Lev | Item | Object | Component no. | Object description | Ovfl | Quantity | Un | Ict | Ex. |
|---|---|---|---|---|---|---|---|---|---|
| .1 | 0010 | | ENGINE1 | 2stroke engine test | | 1 | PC | L | |
| ..2 | 0010 | | T_ENGINE_BLOCK | Engine Block for Thesis | | 1 | PC | L | |
| ..2 | 0020 | | T_CAMSHAFT | Camshaft for thesis | | 1 | PC | L | |
| .1 | 0020 | | ENGINE2 | 4stroke engine test | | 1 | PC | L | |
| ..2 | 0010 | | T_ENGINE_BLOCK | Engine Block for Thesis | | 1 | PC | L | |
| ..2 | 0020 | | T_CAMSHAFT | Camshaft for thesis | | 1 | PC | L | |
| .1 | 0030 | | FRAME1 | dirtbike frame test | | 1 | PC | L | |
| .1 | 0040 | | FRAME2 | cruiserbike frame test | | 1 | PC | L | |
| .1 | 0050 | | FRAME3 | sports bike frame for thesis | | 1 | PC | L | |
| .1 | 0060 | | FRAME4 | touring frame test | | 1 | PC | L | |
| .1 | 0070 | | FRAME5 | standard frame test | | 1 | PC | L | |
| .1 | 0080 | | TYRE1 | pirelli tyre test | | 2 | PC | L | |
| .1 | 0090 | | TYRE2 | goodyear tyre test | | 2 | PC | L | |
| .1 | 0100 | | TYRE3 | MRF tyre test | | 2 | PC | L | |

Figure 21: Super BOM

Now that the super BOM is created, the dependencies will control the BOM explosion from the super BOM based on the configuration done and the dependency rules programmed into the configuration model. This model has a multi-level BOM as the engines are made of 2 raw materials namely CAMSHAFT & ENGINE BLOCK.

### 4.1.6. CREATING SUPER ROUTING

In variant configuration a single routing known as a super routing or super task list can be created for a configurable product although ‘n’ number of variants could be configured from it, this a big advantage compared to a normal scenario where a separate routing has to be created for every material master. If the configuration model contains production at several levels of the BOM then that many routings are needed.

In transaction CA01 the routing for the product TEST1 is created with plant 1000 and the valid key date for the routing is the January 1st of the current financial calendar which in my case is 01.01.2014. The master data for the super routing is partly taken from the material used in the SAP course conducted by the Department of Production at the University of Vaasa, and the object dependencies written in section 4.2.7 will explain how operations are selected after each configuration.

### 4.1.7. DEPENDENCIES

Dependencies are used in BOM explosion, routing operations and also in characteristics and characteristic values. In characteristics and characteristic values the dependency are mainly assigned to ensure the consistency of the configuration i.e. some values might be available only if some specific values are chosen in another characteristic. In this thesis, preconditions are used to check the consistency of the configuration and selection conditions are used to select a particular component from the BOM based on the configuration. The following screenshots shows some of the object dependencies used in this thesis.

*(i) Preconditions:*

The following figure shows that the value ‘RED’ under the characteristic ‘BIKECOLOR’ will be displayed only if the value ‘TYPE1’ is selected under the characteristic ‘FRAMETYPE’. Also if no value is assigned to the characteristic ‘FRAMETYPE’ the value ‘RED’ won’t be displayed.

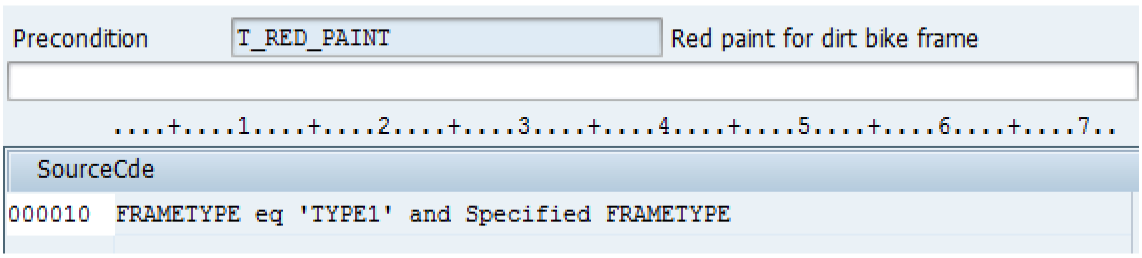



Figure 22: Code for the precondition ‘T_RED_PAINT’

Likewise, a precondition makes sure that the 'TYPE1- dirt bike' can only be possible if a '2stroke' is chosen as the value for the characteristic 'ENGINETYPE'. There are other preconditions created which hide the value MRF for the characteristic T_TYRE if 'STANDARD' bike frame and 'BLUE' color are not chosen. CRUISER, SPORTBIKE, TOURING and STANDARD would be displayed only if a 4stroke engine is chosen.

*(ii) Selection Conditions:*

A number of selection conditions are created in order to pick the correct component and operation for the particular configuration from the BOM and the routing. Almost every value in the configuration model is assigned with a selection condition since every value relates to a different component in the super BOM. The following figure shows the list of selection conditions created related for the configurable model.

| | | | |
|---|---|---|---|
| Sel. cond. | 0000002288 | 1 | Bill of material |
| Sel. cond. | 0000002289 | 1 | Bill of material |
| Sel. cond. | 0000002290 | 1 | Bill of material |
| Sel. cond. | 0000002291 | 1 | Bill of material |
| Sel. cond. | 0000002292 | 1 | Bill of material |
| Sel. cond. | 0000002293 | 1 | Bill of material |
| Sel. cond. | 0000002294 | 1 | Bill of material |
| Sel. cond. | 0000002295 | 1 | Bill of material |
| Sel. cond. | 0000002296 | 1 | Bill of material |
| Sel. cond. | 0000002297 | 1 | Bill of material |

Figure 23: Few selection conditions created for BOMs

### 4.1.8. SETTINGS FOR MATERIAL PLANNING

In standard SAP system production planning is programmed through various complex processes. There are parameters which are maintained at various places in the system in order to allow the user to configure production planning according to their needs. Some of the parameters that play a major role in production planning particularly with a make-to-order process (relevant to the thesis) is 'Strategy group' which is maintained in MRP3 tab of the material master data and the 'Individual/collective BOM explosion' maintained in MRP4 of the material master data. These are the parameters that are maintained by the user while creating master data for the material. Apart from these there are a few parameters that one needs to ensure if they are set correct, they are 'requirement types' and 'requirement classes' for the 'Strategy Group'. As described in the table item category determination under section 3.5.1 the sales order type and the item category group are used together to determine an item category in the sales order. In this case the sales order is OR and item category group is 0002 for configuration, the default item category group will be TAC – variant configuration, this default item category could also be changed manually into TAM – assembly item in the sales order. This default item category group is used to determine requirement types and requirement classes. In this case, the item category is TAC and the MRP type used in the material master is PD- Material Requirement planning, for this combination the requirement quantity is KEK- Make-to-order configurable material. Requirement class is determined based on this requirement type, for requirement type KEK the standard requirement class is 046. Requirement class is the control point between the sales order and MRP. It takes care of availability check and transfer of requirements from the sales order to MRP.

#### 4.1.9. CREATING SALES RELATED DATA

In order to simulate the order delivery process, sales and purchase related data need to be created and used. Initially a customer with the name 'T_customer' is created under sales organization 1000, company code 1000, distribution channel 10 and division 00. The customer comes under 'General Customer' in 'account group'. The customer is fully liable to tax and has a VAT registration number DE123456789. The master data for the customer is taken from the material used for the SAP course conducted at the University of Vaasa. The vendor number used for purchase orders is 100353.

### 4.2. MANUFACTURING COMPONENTS IN THE FACTORY

In order to start manufacturing using the 3D printing first 3-dimensional models were searched and finalized. The finalized models are all stored in the computer attached to the Makerbot replicator in Technobothnia. The engines and frames are easy structures to be printer but the frames are pretty complicated. In order to ensure error free printing the parts are first loaded in the MeshLab software and checked if any holes exist in the models. If present the software allows automatic filling up of holes. Once all the holes are filled and the model is hole-free then it is saved as the final version and loaded in the Makerware software.

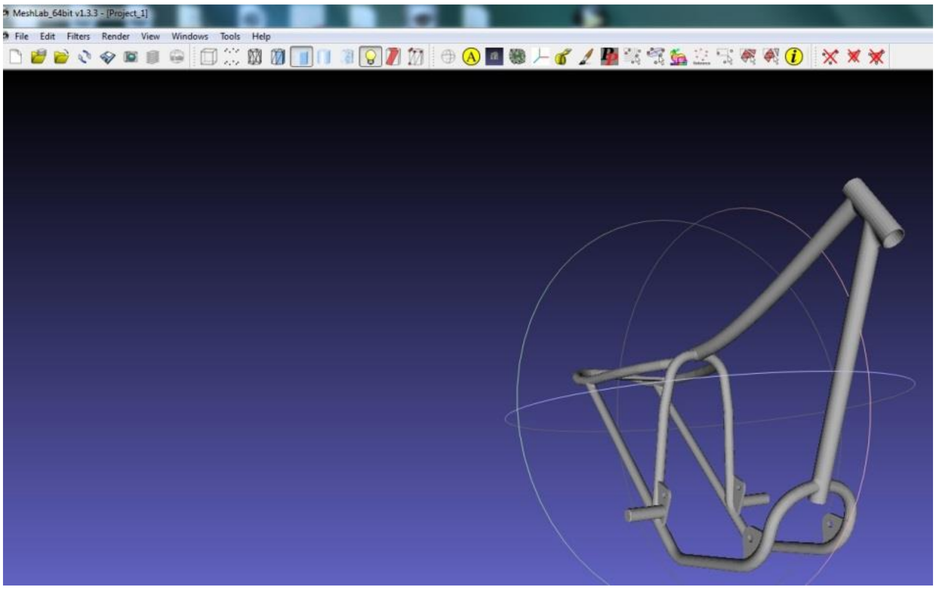



Figure 24: A frame being checked for errors in Meshlab software

A few parameters should be maintained in the makerware software before manufacturing. The main parameters are the support, raft, infill rate and plate temperature. If the object has a flat surface it could be placed with that surface touching the build plate but, if the object is uneven or curved in all the surfaces then it needs supports to be printed. But supports should be chosen only when necessary as it always becomes a tedious job to separate the object from the support and often times the object breaks while doing it. It is advisable to have a raft on the bottom so that the printed object could be removed easily from the build plate. Also it is possible to choose from which extruder the object should be printed or it could be printed using both the extruders also. Usually each extruder has a filament of different color and could be chosen depending on what color the object needs to be printed in. In case of multi-color object it could be printed using both the extruders. The build plate needs to be hot enough in order to keep the object at the same location throughout the printing. It is also necessary to clean the build plate with a proper cleaning liquid after each print. The infill rate decides how much plastic is filled into the printed object if the infill rate is 100% then the object does not have any free space inside and is totally filled with plastic.

After selecting these parameters the model could be converted to the G-code which contains the tool path. The tool path commands the extruder on which direction to move at any given time during the printing. The inbuilt slicer present in the Makerware software converts the .STL 3D model into the G-code. In the earlier versions of the makerware software (It was called Replicator-G then) it was also possible to make changes in the G-code before printing.

A G-Code is a numerical control programming language and is mainly used in computer aided manufacturing. Once when the G-Code is generated the software also shows us the estimated time and plastic for printing and the printing could already be visualized layer by layer. This visualization helps the user in monitoring the printing process and ensures if everything is going according to the plan.

After this the model could be sent to print. It is necessary to ensure that there is enough amount of filament for printing the object. The printing needs to be checked once in a while to make sure everything is going fine. Once when the printing is done the build plate should be left to cool down for a few minutes before the object is removed from it. After removal the object could be separated from the raft and the supports and the raft is cleaned to make sure the surface is completely free from the plastic used to build support. Now the object is ready to be used. All the components that are manufactured to simulate mass customization as implemented in this thesis are displayed as pictures in annexure1.

## 4.3. ESTIMATING PRODUCTION CAPACITY OF THE FACTORY

In order to get a deeper understanding of how this system works and how the arbitrary demand and the errors in manufacturing affects the production capacity of manufacturing the motorcycle the process was simulated using ExtendSim simulation software and estimates were derived on how many motorcycles could be manufactured in a year.

3D printing still remains a nascent technology and the number of errors and failures while printing are quite high which usually increases with the increase in the complexity of the shape of the object being printed. This errors and failures play a major role in determining the production capacity of any manufacturing environment using a 3D printer as a factory. This mass customisation manufacturing system works on pull strategy where the production is completely pulled by a customer order. There is no demand planning used and hence the demand varies quite much. There might be days in which the demand is at its peak and not even a single sales order being created in some other days. After assembly the motorcycles are assumed to be shipped only when a batch number of 20 are reached.

| Scenario | Demand | Number of Batches shipped | Number of motorcycles shipped |
|---|---|---|---|
| Scenario 1 | 10 | 88 | 880 |
| Scenario 1 | 10 | 88 | 880 |
| Scenario 1 | 10 | 87 | 870 |
| Scenario 1 | 10 | 91 | 910 |
| Scenario 1 | 10 | 88 | 880 |
| Scenario 1 | 10 | 87 | 870 |
| Scenario 1 | 10 | 90 | 900 |
| Scenario 1 | 10 | 84 | 840 |
| Scenario 1 | 10 | 90 | 900 |
| Scenario 1 | 10 | 86 | 860 |
| | | | |
| | | 87,9 | 879 |
| | | | |
| | 1 BATCH | = 10 MOTORCYCLES | |

Table 3: Production capacity estimation for every production run

Using the 3 factors mentioned above, a simulation model is built and the average number of products produced in a year is calculated. The simulation is run 10 times and an average value is attained. The results show that approximately 879 motorcycles could be shipped in a year if the average demand in a particular day is assumed as 10 with a standard deviation of 5. This means, everyday 5 to 15 sales orders arrive and there are also days in which no sales orders arrive. A screenshot of the entire simulation is given in annexure 3. The following pages will break the simulation into smaller pieces and describe them in detail.

ASSUMPTIONS MADE:

1. Only one 3D printer is used for manufacturing the entire motorcycle.
2. On an average day the maximum quantity of motorcycles to be printed is 15 and the minimum could be 5.
3. During the first test prints of all the 3D models the frames were complicated to print and it was the component that failed the most number of times. So, in this simulation model it is assumed that the frame has 50% chances of failure wherein the other components like engine and tyre has only 10% chance.
4. Shipping is done in batches, only when 10 products are manufactured then it is taken for shipping.

5. The factory is assumed to run 24 hours a day and 7 days a week.

As mentioned before the demand is arbitrary and there might be days where no demand comes. In order to simulate this demand in the software two factors are used one is the create item icon that generates an order using a normal distribution where 1 indicates an order and 0 indicates no order. The quantity of motorcycles to be manufactured varies between 5 and 15 which is generated through a random number generator with a normal distribution.

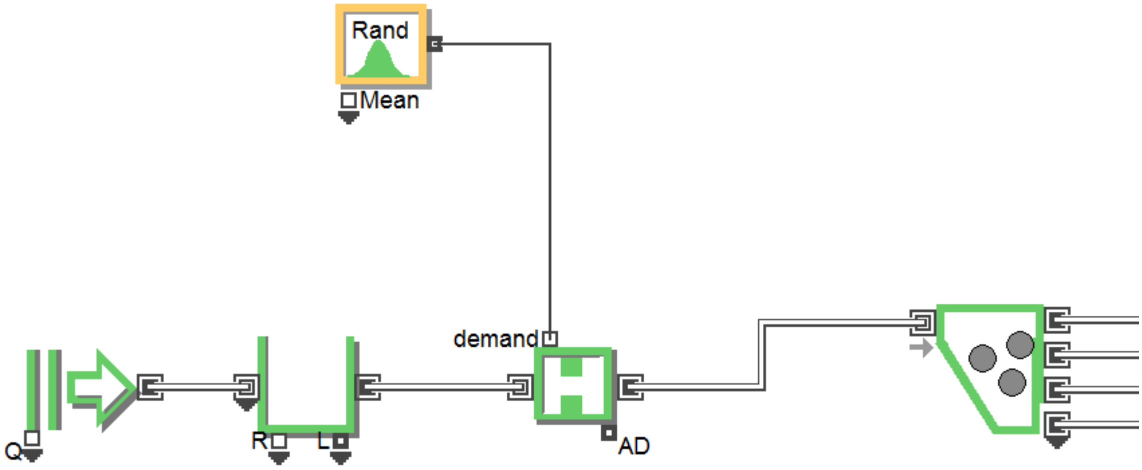



Figure 25: Demand Generation

The actual demand is a product of these two values, if there is a 1 from the create item icon and a random number from the random number generator they are multiplied in the 'gate' and the resultant number is the quantity for that particular order.

Random number generators can generate fractional values also which in real case cannot be taken as a demand. This problem is solved by using the round off method which is done by the 'gate'. In the end every quantity that comes as a demand indicates a complete motorcycle which needs to be divided into its components for manufacturing since frames, tyres, camshaft and engine block are procured as raw material and semi-finished products.

Only one factory (3D printer) is used for manufacturing all the components assuming that all the suppliers use the same factory to manufacture. Although in real life this scenario is highly unlikely to happen is was simulated this way because only one printer was used actually during the whole thesis. Since the frames have a high failure rate it is assumed that for every motorcycle manufactured the frame of it needs to be manufactured at least 2 times. The time taken for manufacturing is set using the experience gained while running the test prints.

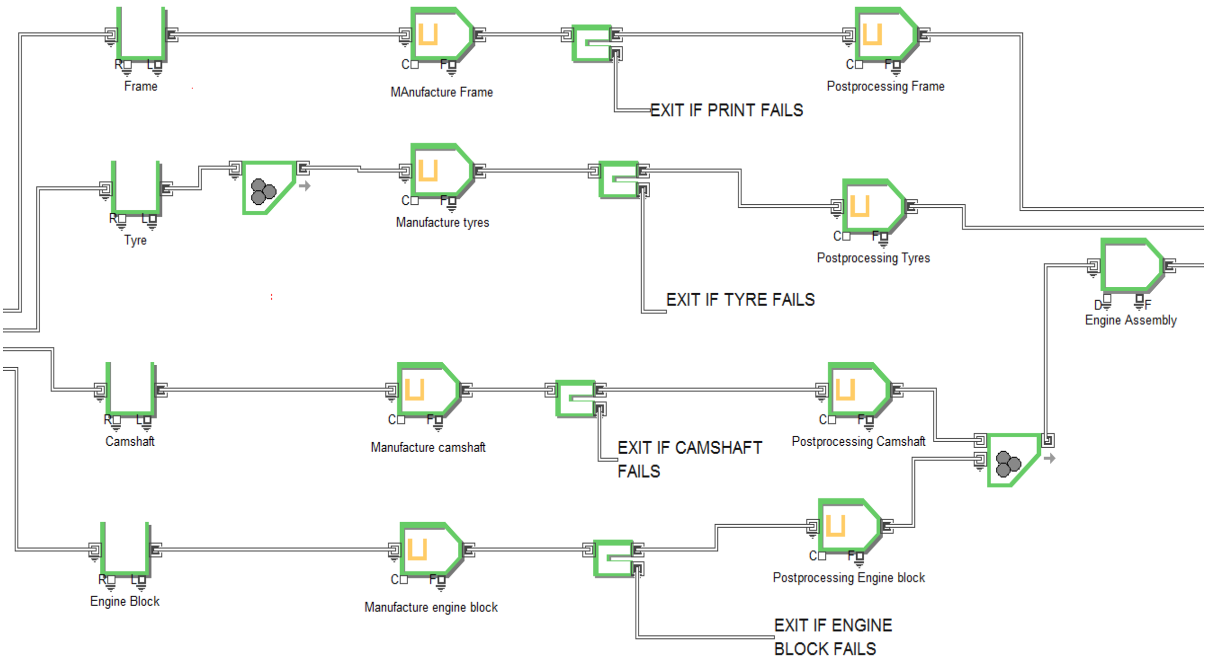



Figure 26: Manufacturing components and post processing them

So it takes 5 hours for the frame to be printed and 1 hour for the tyre to be printed. Since the machine won't be free until the frame is done a manufacturing time of 6 hours is entered for the tyre. Similar addition of manufacturing time is done for camshaft and engine block also. Tyre were usually printed in pairs because there was enough space for it and also because of its similarity in shape. In order to simulate this tyre were batched in 2 pairs before manufacturing. The failure in manufacturing is simulated using the exits. If any failure happens the product exits the system. After post processing the components are ready for assembly.

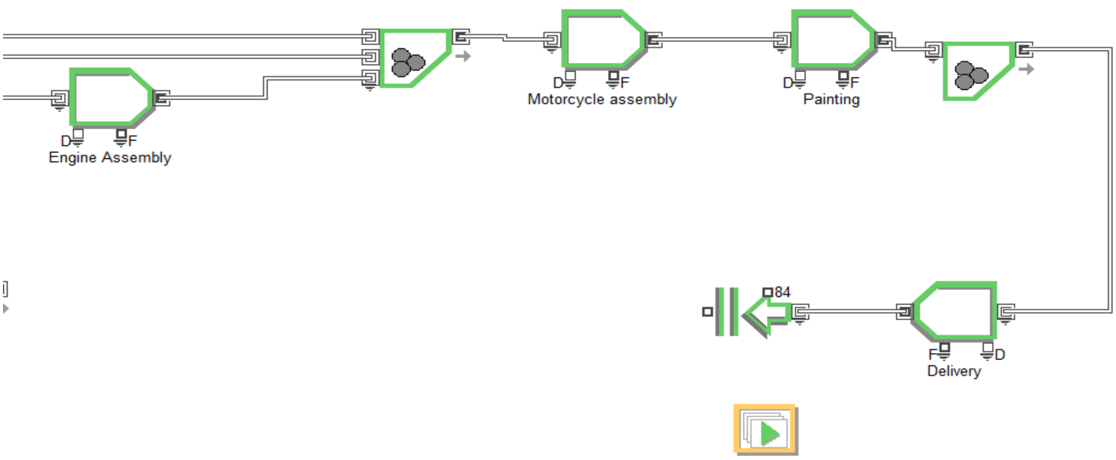



Figure 27: Assembly and Shipping

Further down the process all the components are batched and the motorcycle is assembled then painted and shipped. So the final output numbers indicate the number of batches that are being shipped.

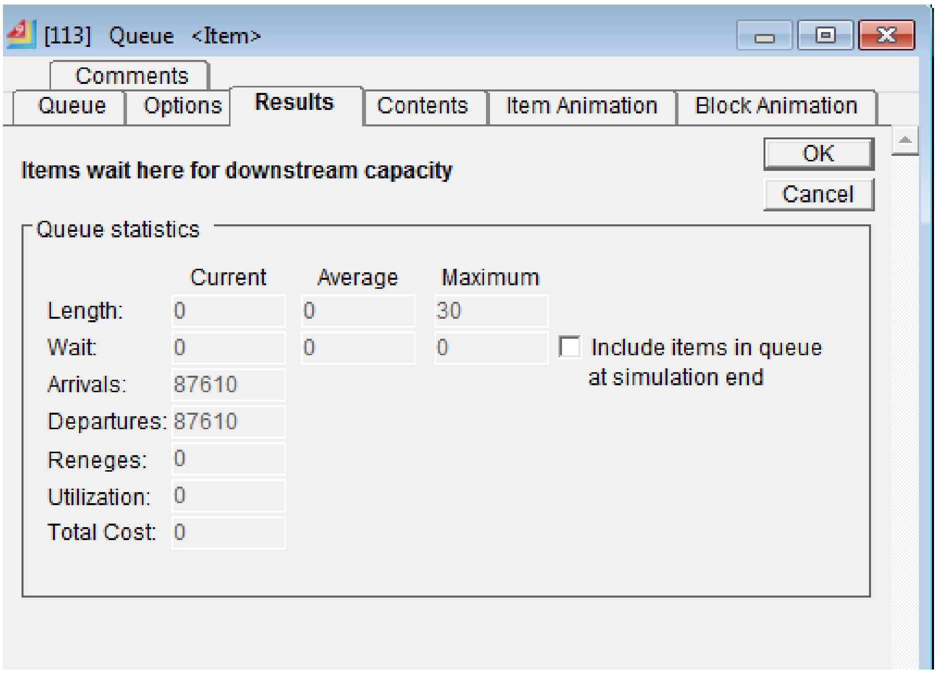


Figure 28: Queue status showing number of orders placed by customers

# 5. RESULTS AND DISCUSSION

## 5.1. SIMULATING MASS CUSTOMIZATION

In order to simulate mass customisation as implemented in this thesis the following step wise procedure needs to be followed. The motorcycle is made-to-order hence a sales order starts the process with the customer customizing the motorcycle in the product configurator created using SAP variant configuration in section 4.2. The sales order created using the product configurator contains the required BOM items for the manufacturing of the particular product. The manufacturer manufactures the motorcycle using production order for in-house manufacturing and purchase orders for externally procured parts/components. The process ends when the manufacturer has made enough quantities of the motorcycle that the customer ordered through the sales order created in the first step.

*STEP1: Sales order Creation*

In transaction VA01 a sales order of type ‘OR’ is created for the material ‘test1’ after entering the quantity and hitting enter, the system redirects to the configuration screen where the material is configured and the following BOM and routing values are selected.

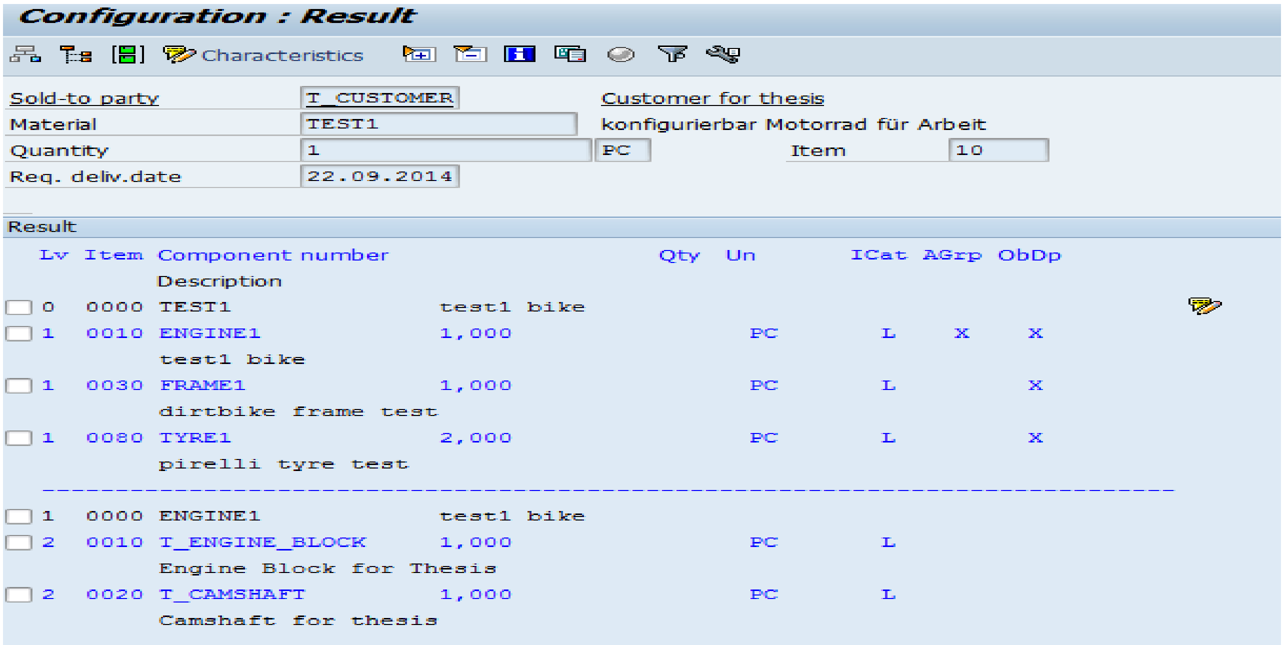
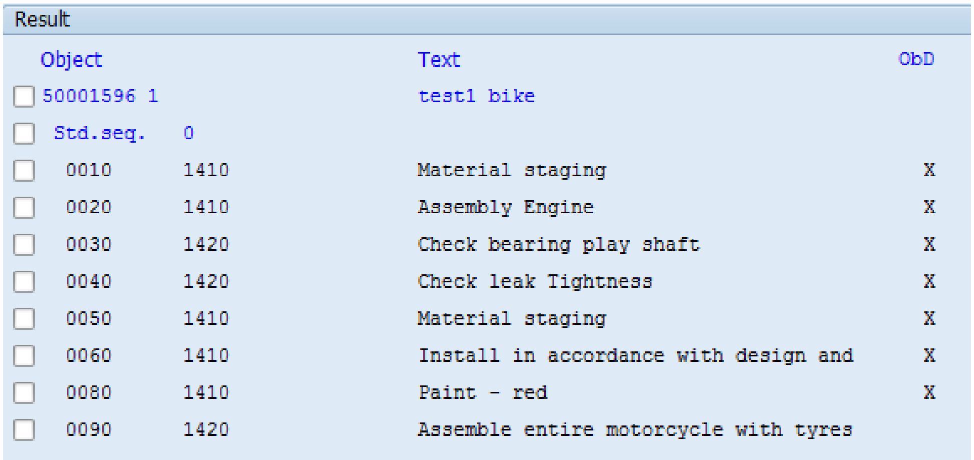



Figure 29: Only the necessary items being selected from the super BOM



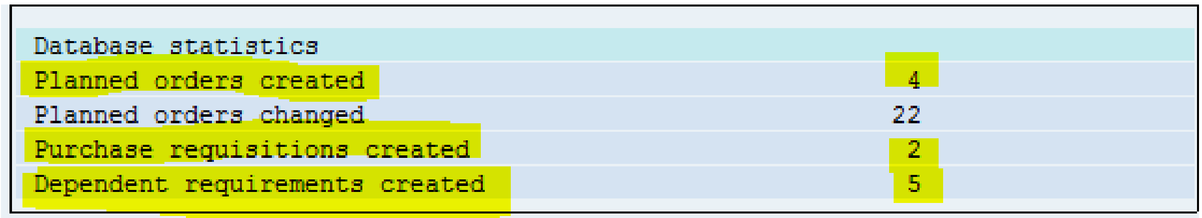
| Object | | Text | ObD |
|---|---|---|---|
| 50001596 1 | | test1 bike | |
| Std.seq. | 0 | | |
| 0010 | 1410 | Material staging | X |
| 0020 | 1410 | Assembly Engine | X |
| 0030 | 1420 | Check bearing play shaft | X |
| 0040 | 1420 | Check leak Tightness | X |
| 0050 | 1410 | Material staging | X |
| 0060 | 1410 | Install in accordance with design and | X |
| 0080 | 1410 | Paint - red | X |
| 0090 | 1420 | Assemble entire motorcycle with tyres | |

Figure 30: Correct operations being selected from super routing

The sales order is saved, the order number is 14593 and the order quantity is 1.

*STEP2: MRP Run*

In transaction MD02 MRP is run for the material test1 which creates 4 planned orders, 2 purchase orders and 5 dependent requirements. The 4 planned orders are for the header material test1, the BOM materials engine1, frame1 and tyre1. Since engine 1 is an asembly item the MRP run creates 2 purchase requisitions for the components/raw materials T_camshaft and T_engine_block. All the first and second level BOM items will have a dependent requirement created for it. The following table and the figure shows the results of the MRP run.



| Database statistics | |
|---|---|
| Planned orders created | 4 |
| Planned orders changed | 22 |
| Purchase requisitions created | 2 |
| Dependent requirements created | 5 |

Figure 31: Results of the MRP run

| S.No | Result of MRP run | Component |
|---|---|---|
| 1 | Planned order | Test1, Engine1, Frame1, Tyre 1 |
| 2 | Purchase requisition | T_camshaft, T_engine_block |
| 3 | Dependent requirement | T_camshaft, T_engine_block, engine1, frame1, tyre1 |

Table 4: components involved in the MRP run.

*STEP 3: Converting planned orders into production and purchase orders*

In transaction MD04 the planned order created for the material 'test1' is converted into a production order with order number 60003824. In the same transaction the planned order for the BOM item 'engine1' is converted into a production order of number 60003825.

For the material tyre1 the planned order is first converted into a purchase requisition and then into a purchase order of number 4500018079. The material frame1 already has a stock of 1 in the system so no purchase order was created for this.

*STEP4: Convertng purchase requisitions into purchase orders:*

In transaction MD04 the purchase requisitions for the T_camshaft and T_engine_block are converted into a purchase order under purchasing organization 1000 and the vendor 100353. Purchase order number created for T_camshaft and T_engine_block are 4500018077 and 4500018078 respectively.

*STEP5: Manufacturing the components:*

The parts engine, frame and tyres are printed in the desktop 3D printer. The models used for printing are all stored in the computer attached to the printer. Depending on the configuration the 3D models of the corresponding engine, frame and tyre is chosen and loaded to the Makerware software. After that parameters like the temperature of the build plate, the thickness of the parts, support structures etc are set and the manufacturing begins. The manufacturing process is assumed to be complete once the necessary components are available in the required quantity.

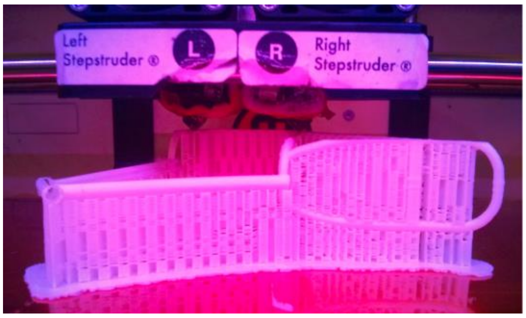


Figure 32: Dirtbike frame being manufactured

*STEP6: Goods Posting for all production and purchase orders:*

Now that the components are manufactured and delivered by the suppliers they need to be posted against the purchase orders in transaction MIGO. The 'items ok' check mark is slected for all the materials in transaction MIGO as an assurance that all the received components are of good quality.

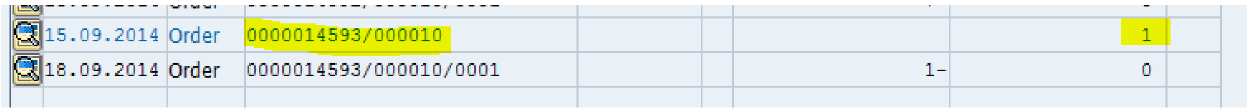
*STEP7: Final assembly and confirmation of production orders*

We now have all the required components for assembling the motorcycle. Hence the materials are staged as below and final painting and assembly is carried out.

Figure 33: Material staging for final assembly and painting

Figure 34: Motorcycle ready to be delivered.

After the assembly of engine and then the motorcycle we can confirm both the production orders for the engine as well as the motorcycle. So, in transaction CO15 first the production order for the material engine1 is confirmed using the production order number 60003825 and for the header material 'test1' it is confirmed using the production order number 60003824. Upon confirmation the system gives an update saying "Confirmation saved (Goods movements: 4, failed 0)" which means 4 materials namely test1, engine1, frame1 and tyre1 are confirmed. As the final step transaction MD04 is checked to confirm if enough quantity is produced against the sales order. The system displays an available quantity of 1 against the sales order 14593 which was created in the initial step. The following figure describes it.



| | | | | | |
|---|---|---|---|---|---|
| 15.09.2014 | Order | 0000014593/000010 | | | 1 |
| 18.09.2014 | Order | 0000014593/000010/0001 | | 1- | 0 |

Figure 35: Highlighted text indicates 1 motorcycle is manufactured against the sales order and is in stock

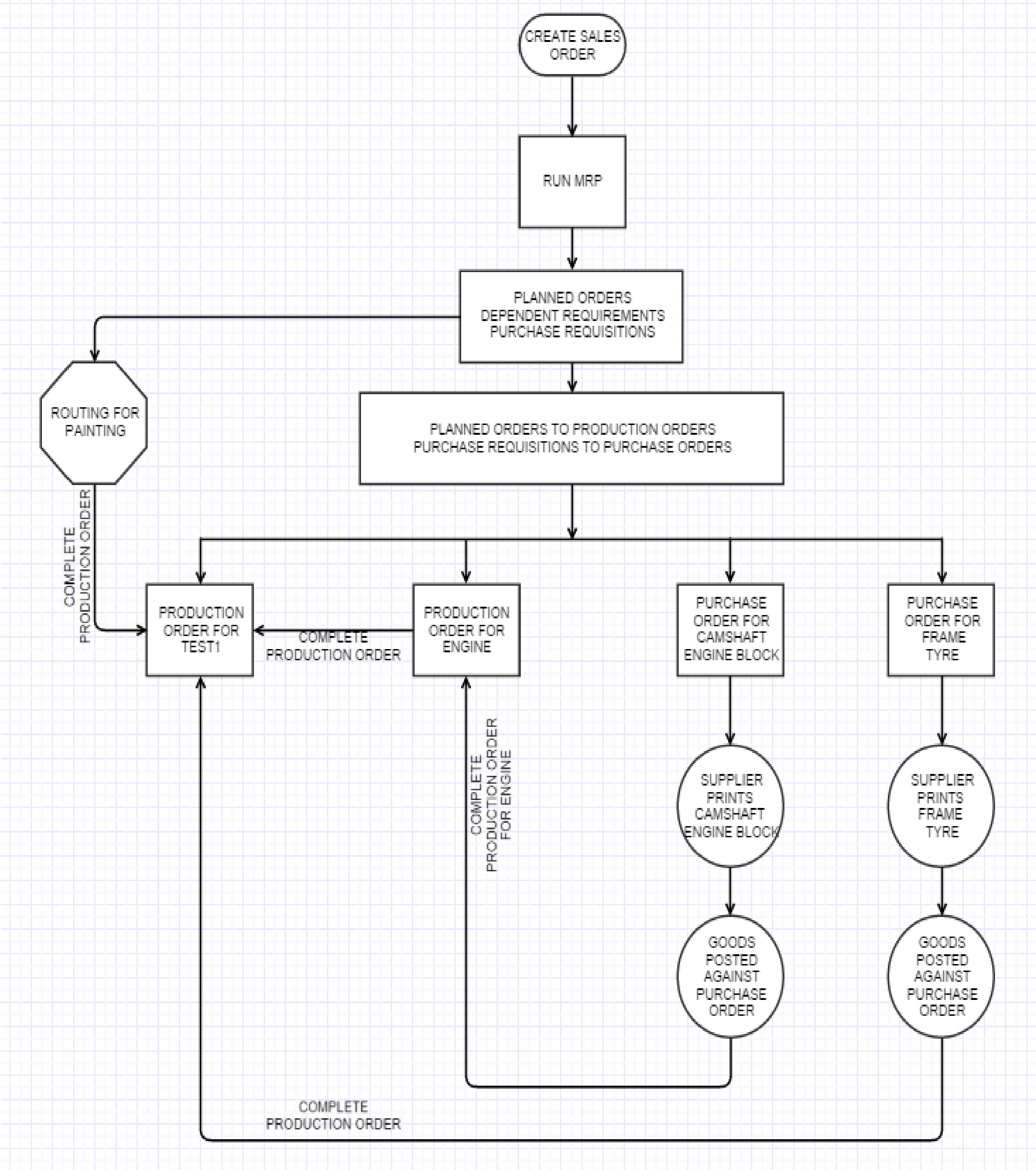



Figure 36: Process flow of the simulation

## 5.2. DISCUSSION

For the manufacturing system implemented in this thesis the product configurator and the flexibility of the manufacturing process are the two main enablers. The flexibility of the 3D printer used as a factory allows the manufacturing of any product, only implication is that the 3D models for the components are ready in .STL format. As mentioned in section 3.2.2 manufacturability of the product family was analyzed during the initial phases of the thesis, by selecting a product for which 3D models are easily available. The average time taken to manufacture one component would be approximately 3 hours. The total time for manufacturing the complete product would be approximately 2 days adding all the possible errors that might come up during manufacturing and post processing steps needed after manufacturing. As the technology of 3D printing develops the speed and quality of printing will increase which will definitely reduce the lead time to manufacture a single product.

When compared with the order fulfillment process studied by Tiihonen and Soininen the SAP variant configurator allows definition of both the sales and technical configuration models and both these configurations could be completed in one step. After which MRP is run and then the production and procurement processes are carried out as per the organizations business process. Although the configuration model developed in this thesis does not have a traditional sales configuration process where the user answers questions to find a perfect match of his product from the manufacturer's portfolio this step is substituted by the value assignment step during the sales order creation. After that the configurator generates the BOM and routing operation which is further used for purchasing and the production and final assembly but this could only happen if the configuration is carried out completely and consistently in the sales order. The configuration system is completely automated in this case, which is very efficient for products with low complexity as used in this thesis, but if the complexity of the product increases then the configuration process would require human intervention and the system will be semi-automated. Using this demonstration system any user could understand that 3D printer have more applications than just rapid prototyping. The user can also get an idea of mass customisation and the essential components that enable manufacturing of customized products in high volumes.

According to the ExtendSim simulation model although in one year approximately 87000 quantities of motorcycle were ordered by the customers, an extremely low quantity of 870 were only shipped despite the fact that the factory runs 24 hours a day and 7 days a week. This problem is partly due to the failures that could happen while manufacturing. Still the failures are relatively low because the number of number of products that failure is 1319 only. The main reason is the capacity limitation of the printer and also because only one printer was used for manufacturing all the products. In this case the percentage of customer orders being shipped is 1% which is an unacceptable number in real life and definitely needs to be improved.

## 6. CONCLUSION

Allowing customers to configure their own products is not seen as a value addition anymore. As market competition increases companies cannot consider the markets to be homogenous rather accept the fact that every customer's need differs from each other and this difference in need creates a heterogeneous market. Mass customisation is considered an effective strategy to operate in this heterogeneous market. High volume manufacturing cannot be combined with craft production so, instead of producing what exactly the customer wants companies rather need to find a product as close as possible to the customer's need. To do this companies need a well-planned product platform which is built based on thorough market research and manufacturing technologies that are flexible enough to support product variety. Additionally the company's sales force should be effective enough to understand individual customer needs and use information systems to find if their company's products could be an optimal solution to satisfy this need. Moreover knowledge about market needs from the sales personnel should be documented properly and transferred to the product development team to make changes in the existing product platform.

This thesis started with the idea of demonstrating mass customisation manufacturing and how the information flows within the ERP system in this manufacturing context. As a result any user involved in this simulation could get hands on knowledge of using SAP ERP system and a product configurator while gaining basic understanding about 3D printing technology. The applications of 3D printing technology are enormous, ranging from hobbies to stem cell research. It has become an inevitable technology of the current decade and will be disruptive in the future.

The current system only allows make-to-order and assemble-to-order manufacturing which could be developed further in order to allow order-BOM through which, product variants that doesn't fall within the current configuration model could be configured and manufactured. After this development the configurator will allow engineer-to-order manufacturing also. A knowledge repository could also be added to the configurator that could store all the sales order related data which could further be analyzed and customer requirements and order frequencies could be predicted. From the simulation it is understood that in order to make the factory efficient all the 3D printers in Technobothnia should be combined together, machine scheduling should be done to select which machine to be used for which component at that particular time and the factory should be optimized. Optimization of this new factory could be done again by building a simulation model in ExtendSim considering all the 3D printers as factories and measure how they react to unpredictable demands for unpredictable products. Factors like the percentage of customer orders shipped on time, percentage of manufacturing defects, and how much profit could be made in a certain period of time can be calculated from this model. The inputs for the model should be the cost of raw materials, quantity of raw materials needed to manufacture a particular product and the time taken to manufacture it along with the labor costs.

Variant configuration is mainly used by industries that manufacture complex products for example elevators, heavy duty automobiles in mining and construction industry etc. With the inherent flexibility that variant configuration allows, same products could be used in different production and sales scenarios. For example the same product might be manufactured and sold in different ways in different countries according to local laws and regulations. This could be done by applying different configuration profiles to the same product. This configuration type could be used for batch production and job order based production where the product variety is high but the volume of production and uniformity of produced products are low. Because customers demand high variety, set up times might be higher in this kind of production but it could be kept as low as possible with proper production planning.

Implementing variant configuration in an organization is a multi-level complex topic which needs visualizing the forth coming problems related to both product data maintenance and business process associated with the supply chain and analyzing and planning solutions for it. To start with, like in any project the goal of the management in the organization should align with the goal of the project team for the success of the VC implementation project. In order to start working, the organization needs in-house SAP VC experts or external consultants to work with the product development, sales, planning, supply chain management, and production teams from the beginning of the project. One of the main inputs for this project would be the product model which contains information about what type of products are used, the business processes related to manufacturing the end product for example which components are manufactured in-house and which are purchased etc. This basic information will help create the master data and configuration rules and restrictions in SAP ERP. In order to implement VC the standard SAP system needs to be customized according to the organization’s needs. This customization includes material master customization and customization related to logistics and classification system. In this customisation phase, planning strategy of the product needs to be identified, authorizations need to be maintained, item category, and item class etc. needs to be determined. Similar to other SAP implementation projects, communication within the team and all the other stakeholders involved in the project on the organizational level is a key factor in ensuring success in this project. Once when the product model is created possible bottlenecks that could occur during the configuration process should be predicted and efforts should be put in order to overcome the system performance problems that these bottlenecks bring along. The configuration process should also be tested with real-life scenarios in which the user will use it. Since customer needs and the product structure keeps changing, change management is very important in VC projects. In standard SAP system master data changes could be maintained and monitored using ECM (Engineering Change Management) and production order changes could be maintained and monitored using OCM (Order Change Management). Also end users of the configurator in various departments of the organization needs to be trained about how to use the configurator and how their work will change from the current method after the configurator is implemented. It is also beneficial to keep them updates about the possible changes in their work from the beginning of the VC implementation project in order to avoid any last minute friction and disagreement between the employees and the management. Similar to other SAP implementation projects VC projects are also first tested in a testing system and then implemented in the live production system.

As explained in the theory section of this thesis, flexible manufacturing process is an enabler of mass customisation. A 3D printer could be considered as a very flexible factory that could manufacture product of any shape although every 3D printer has a limitation on the size of the product they could manufacture. 3D printing seems very much suitable for products with low demand and high personalization needs. Once when the design part of the product is done then it could be manufactured in various quantities according to the customer’s dimensional and other visual needs. Product whose design is finalized can still be changed further and allow further customisation and along the same time these changes could be recorded in the configurator for future use. A few examples of these products could be dental implants, micro chips and processors, integrated circuits, small parts like screws and bolts, parts for electronic gadgets like computer cabinets, mobile phone cases etc. The applications of combining 3D printing and product configurators in mass customisation manufacturing is already enormous and will increase more with the further development of both these technologies.

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## ANNEXURE1: ADDITIONAL PICTURES RELATED TO 3D PRINTING


Picture of the Makerbot 3D printer used as a factory in the thesis

Image of engines: four stroke engine (top) two stroke engine (bottom)

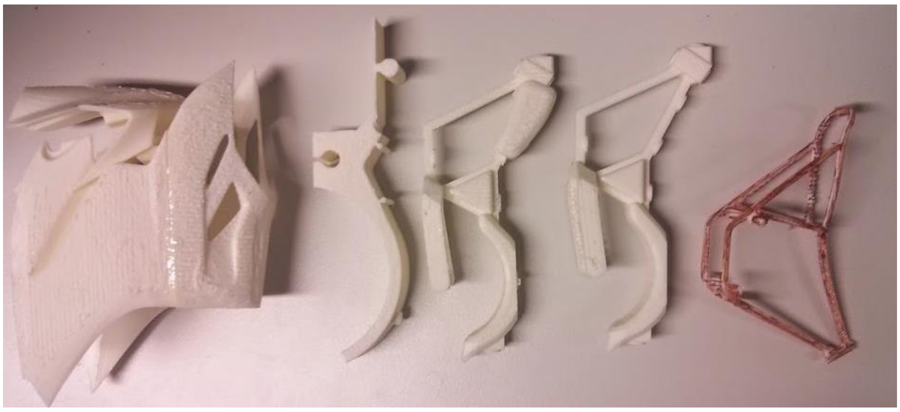
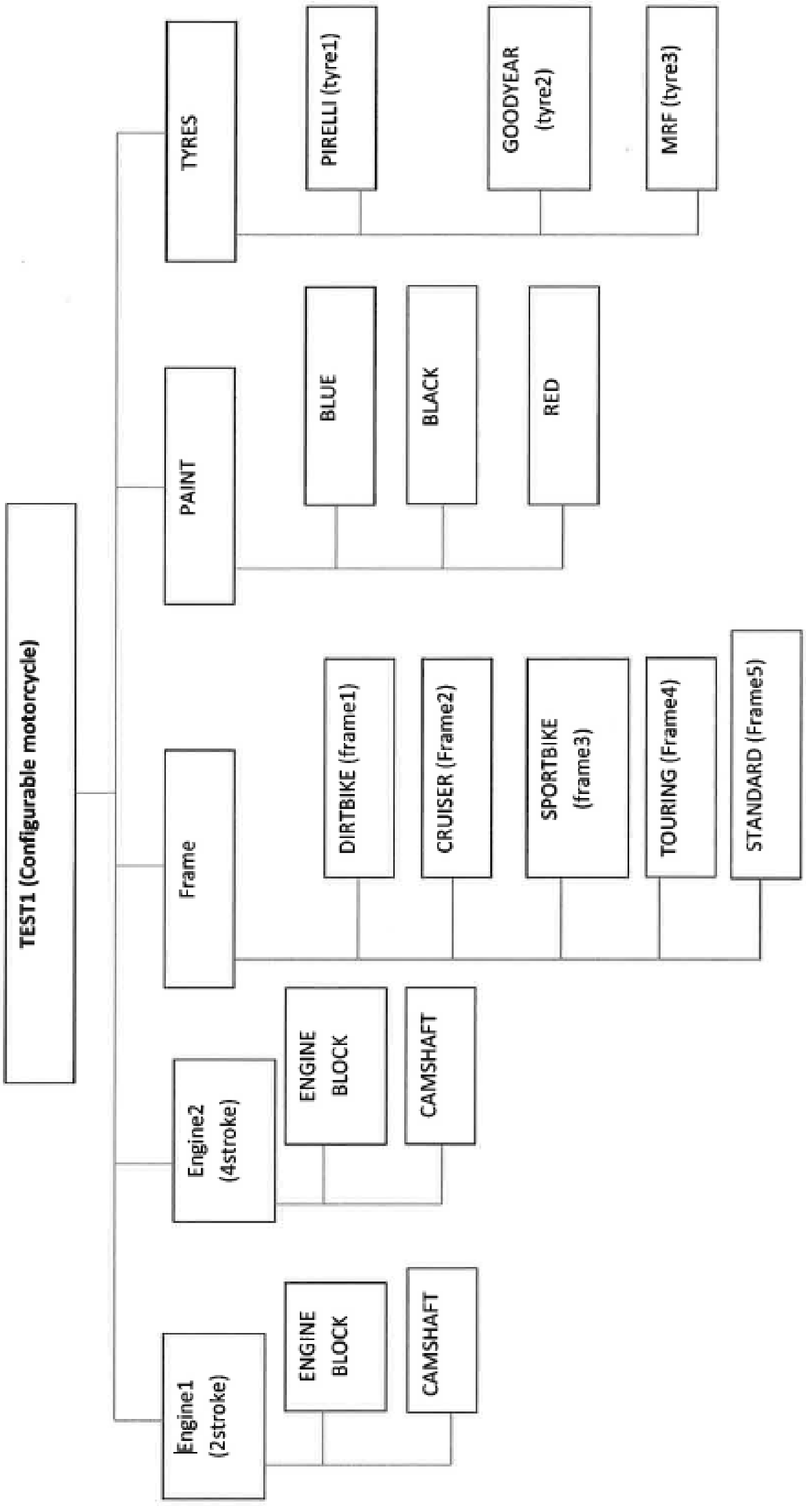


Image of Frames: from left to right sports frame, standard frame, touring frame, cruiser frame, dirt bike frame

Image of tyre from left to right Goodyear tyre, Pirelli tyre, MRF tyre

**ANNEXURE 2: COMPLETE STRUCTURE OF THE CONFIGURATION MODEL**



## ANNEXURE 3: SIMULATION MODEL FOR PRODUCTION CAPACITY ESTIMATION