

Simulation with 3DEXPERIENCE

Evaluation of software for production flow simulation in manufacturing industry

Master's thesis in Production Engineering

Erik Bernérus
Marc Karlsson

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manufacturing industry

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CHALMERS
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Department of Product and Production Development

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Gothenburg, Sweden 2016

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Cover: 3DEXPERIENCE compass, see subsection 1.1.2.

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Abstract

This thesis treats the production flow simulation capabilities of the software 3DEXPERIENCE by Dassault Systèmes, which is a holistic Product Lifecycle Management system. The software 3DEXPERIENCE's *Industrial Engineer* and *Manufacturing Engineer* roles have been thoroughly tested and evaluated. The evaluation method used has been revised to better fit today's standards and demands on production simulation software, as seen by a large enterprise. After comprehensive research and learning of the software, a simulation model was constructed, which lent aid for the evaluation of the software. The simulation model depicts a part of the production line of a large enterprise, Toyota Material Handling; a company which has served as a reference company for large enterprises in this thesis. The simulation model showcases the possibilities that 3DEXPERIENCE offers in terms of production simulation. The outcome of the evaluation was that 3DEXPERIENCE excels in evaluation categories such as *visual aspects*, *efficiency*, *modelling assistance* and *user support*, but clearly lacks in categories such as *financial and technical features*, *statistical features* and most notably, *environmental consciousness*. Furthermore, the thesis contain instructional guides explaining how the different apps within the aforementioned roles operate in reference to one another.

The thesis work has been carried out in cooperation with Swedish consultancy firm *Prodtex*, as it was in their interest to attain a broader knowledge base regarding production flow simulation within 3DEXPERIENCE.

Keywords: Production Flow Simulation, 3DEXPERIENCE, DELMIA, Dassault Systèmes, Discrete Event Simulation, DES, Evaluation of simulation software

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List of Abbreviations

2D - Two dimensional
3D - Three dimensional
AHP - Analytic Hierarchy Process
BCL - Batch Control Language
BT - BT Products AB
CAD - Computer Aided Design
CAM - Computer Aided Manufacturing
CPU - Central Processing Unit
DES - Discrete event simulation
DHM - Digital human models
FAHP - Fuzzy Analytic Hierarchy Process
GPU - Graphics Processing Unit
IEN - Industrial Engineer, role in 3DEXPERIENCE
LCA - Life Cycle Assessment
MBOM - Manufacturing Bill Of Materials
MCDM - Multi-Criteria Decision Making
MEN - Manufacturing Engineer, role in 3DEXPERIENCE
MTBF - Mean Time Between Failures
MTTR - Mean Time To Repair
NC machine - Numerical control machine
OS - Operating system
PDM - Product Data Management
PLM - Product Lifecycle Management
PSI - Preference Selection Index
SCL - Simulation Control Language
TMH - Toyota Material Handling
TMHG - Toyota Material Handling Group
TOPSIS - Technique for Order Preference by Similarity to Ideal Solution
app - application, a distinct part of the 3DEXPERIENCE platform
e.g. - *exempli gratia* (for the sake of example)
et al. - *et alii* (and others)
etc. - *et cetera* (and so forth)
i.e. - *id est* (that is)

1

Introduction

This chapter serves to provide an overview of the importance of simulation software and the use of such software.

1.1 Background

Continuous improvement is vital in order to stay ahead of the competition and retain a high efficiency [1, p. 282]. In manufacturing, shutting down an entire production line in order to carry out potential improvements is a risky thing to do. Not only does the proposed improvement cost money to implement, but while implementing the change there will also be a loss of potential profit that the production line would generate if it was still in use, not to mention the loss of capital in the long run if the implemented improvement does not work as expected. These are some of the reasons why being able to simulate a production line has been of such great importance the last decade, and will most likely continue to be so [2, p. 23]. With simulation, it is possible to mirror the behaviour of a production line and see the improvement potential of a proposed change without interfering with the daily production [3]. Simulation can also be used to design and validate a new production system [4, p. 123-124]. This reduces the need of physical testing and programming thus shortening the lead time from design to running system. While simulating in production is nowadays a wide-spread and ordinary undertaking, companies may find it valuable to keep their software up-to-date.

The current mature production flow simulation software available on the market by Dassault Systèmes is called QUEST, which in turn is a part of the DELMIA platform. As DELMIA was released in 2000 [5], the software is considered dated which is one of the reasons why Dassault Systèmes has developed a new software which consists of a number of *apps* distributed onto roles such as *Industrial Engineer* and *Manufacturing Engineer*, which in turn are parts of a platform of software tools known as 3DEXPERIENCE.

While switching the simulation software used in a company can certainly yield several benefits, it is also a costly and risky endeavour.

1.1.1 QUEST

One of the predecessors to 3DEXPERIENCE is called QUEST. It was originally developed by Deneb Robotics, a company which was acquired by Dassault Systèmes in the year of 1997 and re-branded as DELMIA [6].

The idea behind QUEST is to provide a tool for Discrete Event Simulation (DES)¹ where the user can switch between a conceptual 2D view and a more thorough 3D view [7]. In QUEST, the user is able to either select geometries one wishes to use in their simulation, or create their own. It is possible to describe each geometry's own behaviour to then execute the simulation which will render the user an output in several different parameters for each element in the simulation. The user can specify changes and improvements to review the possibility of changing their actual production system.

QUEST is, in a way, semi-open source. The user can manually write new or modify the behaviour of the elements that are being used, using the built-in Simulation Control Language (SCL). In the same way, the user can modify the simulation runs by specifying the behaviour of multiple series of runs using Batch Control Language (BCL). QUEST can be used as a single software to simulate a virtual production system, but it can also be used in cooperation with other software such as UltraArc, ERGO, Envision, among others [7].

1.1.2 3DEXPERIENCE

Dassault Systèmes describes 3DEXPERIENCE as a *"Business Experience Platform"* [8] that can be *"available on premise and in public or private cloud"*[8]. This means that 3DEXPERIENCE has a unified interface that serves the different applications and give access to the data needed for the different roles in a company. It hosts applications relevant to 3D modelling, simulation, collaboration and information intelligence, as seen in Figure 1.1. As shown in Figure 1.2, the 3DEXPERIENCE platform exceed a *Product Lifecycle Management* (PLM) system by providing a holistic view with the customer in centre, instead of the product. By doing this, 3DEXPERIENCE provides a deeper understanding of the customer and the functions of their product for the user of 3DEXPERIENCE.

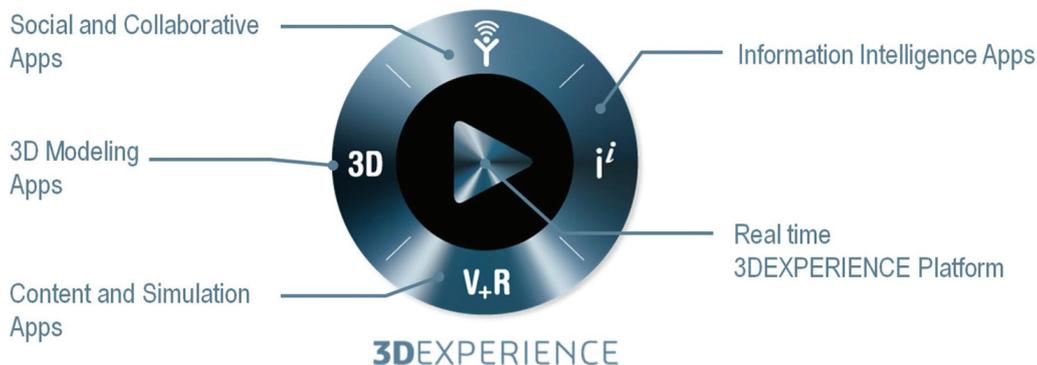


Figure 1.1: The 3DEXPERIENCE compass tool for navigating the interface. Figure reproduced with permission of Dassault Systèmes AB. (Source: Dassault Systèmes [9])

¹DES is event based simulation where events update the state of the system.

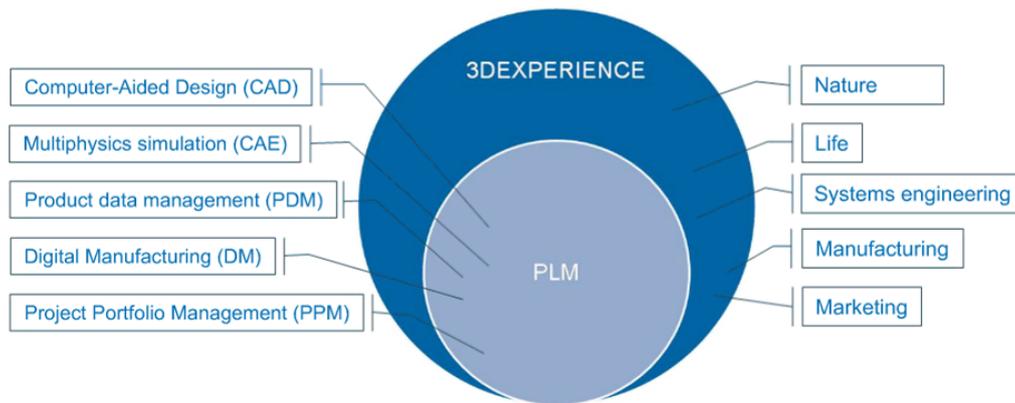


Figure 1.2: The concept of the 3DEXPERIENCE platform. Figure reproduced with permission of Dassault Systèmes AB. (Source: Dassault Systèmes [10])

1.1.2.1 Data-driven

3DEXPERIENCE is a data-driven software. This means that there is no traditional file system in place, all product related information is stored as data on a central location. Authorized users who are in need of utilizing the data can continuously stream the data to their workstation while working with it.

Traditional *Product Data Management* (PDM)² systems require the user to check-out the file they want to work with and by doing so prohibiting others to work on it at the same time [11, p. 237]. A problem that could occur is when there are several users that check-out different files under the same parent. If the first user check-in their edited file and update the parent, the next user who is going to check-in their edited file will have a problem with the parent file having been updated and the change that was made may not be compatible with that of the new parent file. 3DEXPERIENCE solves this problem by letting the users stream the data they need directly to the work station and as soon as they update the data it is streamed back and updated centrally. As 3DEXPERIENCE is data-driven, the parent only has links to the data of the children and therefore is directly updated with no file version clashes.

1.1.2.2 Collaborative work

The 3DEXPERIENCE platform is designed for collaboration. Several users, ranging from one and up, can in real-time access and manage the data they need at the same time. For example, an employee can check how a part fits in an assembly while the supplier changes the dimensions of the part. If anything clashes, both parties will receive a message on their work-screen with information about the clash. 3DEXPERIENCE has also made it easier to convey clashes to the relevant parties. The user who finds a clash in an assembly can review the clash, mark the problem and send it to the relevant party. When the user receive an updated version of the part that clashed, the user can overlay it with the old part to review the changes and then import it into the assembly and confirm that the clash is resolved.

²PDM, a function within PLM to manage product data.

3DEXPERIENCE incorporates a project management application that their users can use to follow the progress of a project. They can, in real-time, see what is needed to be done to complete different parts of the project. It is also possible to send and receive messages from other collaborators on the project.

1.1.3 Toyota Material Handling

In order to validate 3DEXPERIENCE from a real-world scenario a part of Toyota Material Handling's factory in Mjölby was to be simulated. Toyota Material Handling (TMH) also served as a representative of large enterprises involved in production flow simulation.

1.1.3.1 Mjölby factory

The factory in Mjölby, originally called BT Products AB (BT), is nowadays referred to as Toyota Material Handling Sweden. Toyota purchased BT Products AB in the year of 2000 and they are now part of Toyota Material Handling Group (TMHG) [12], although they still use the BT brand on their hand pallet trucks.

BT was founded in 1946 and produced their first hand pallet truck in 1948, see Figure 1.3 [12]. In 1949, BT in collaboration with Statens Järnvägar (SJ) developed the EUR-pallet, which has become the standard pallet in Europe [12]. BT established the factory in Mjölby in 1968 [12]. In the years 1988 and 1997, BT acquired subsidiary companies in North America and in 1999 another factory in Italy [12].

The factory in Mjölby consist of three divisions: Powered Warehouse Trucks, Hand Pallet Trucks and Spare Parts [13]. The factory is spread-out over 76 000 m^2 and employs 1 850 workers [13].



Figure 1.3: BT's hydraulic pallet truck with a swivelling steering column from 1948.

1.1.3.2 Usage of simulation software

During the execution of this thesis, the simulation engineers at the factory in Mjölby utilize QUEST in order to simulate parts of the production line while considering future investments, interviewee Hoa Hai Gieng, simulation engineer at Toyota

Material Handling, states. While investigating, in order to gain support for a decision, capacity, bottlenecks, buffer sizes etc. are examined. Hoa Hai Gieng further states that QUEST can be a very powerful tool for such a purpose, especially in the matters of programmability and visual representation. However, as QUEST is a software which requires extensive lines of coding, it may be time consuming for the employees at Toyota Material Handling as there is a lack of predefined features as well as QUEST's 3D platform being incompatible with the platform used by the construction department.

1.2 Problem formulation

As one of Prodtex's³ business areas is being a retailer of CAM software, 3DEXPERIENCE may or may not become a valuable software for them to sell in the future. But in order to do so, and to come off as a serious contender in the industry, it is important that they, as a retailer, has sufficient knowledge and experience of the software to be able to tell with confidence whether a customer would have use of the software or not. Selling a software without sufficient knowledge can have serious repercussions for the company, as they put their reputation at stake. If they would proceed to sell the software, only to later find out that the customer has no use of it, it is unlikely that said customer would approach the company for further business in the future. On the other hand, if they would hesitate to sell the software to the customer, even though the customer could make proper use of it, they would lose out on a considerable sale while also risking that the customer ties connections to one of their competitors.



Figure 1.4: Prodtex's logotype.



Figure 1.5: Toyota Material Handling's logotype.

1.2.1 Purpose

In order to mitigate the risks of the scenarios previously mentioned in section 1.1 and 1.2, the sound solution is to investigate the software to be able to confidently tell if the customer, depending on its needs, will have use of the software or not. The knowledge that the company will gain also has an effect on their ability to cater to the needs of future customers who also may show interest in the software. Therefore, there exists an interest from their part to evaluate the capabilities of the software 3DEXPERIENCE, which is currently in development. More precisely for this thesis, the capability of production flow simulation within the 3DEXPERIENCE platform will be examined.

³Prodtex is a consultancy firm that has a partnership agreement with Dassault Systèmes to sell and market DELMIA products in Sweden, Denmark and Norway [14].

1.2.1.1 Research questions

The project aims to answer the following questions:

1. Is it possible to evaluate 3DEXPERIENCE using a scientific method and if so, how would 3DEXPERIENCE fare in such an evaluation?
2. Is 3DEXPERIENCE suitable for large enterprises?
3. Does the sustainability features of 3DEXPERIENCE match the demand on such features at large enterprises?

1.2.1.2 Additional targets

The thesis work should also include:

- A factory flow simulation based upon parts of the production flow from a kitting station prior to welding, to a buffer station prior to painting at the Toyota Material Handling factory.
- An investigation of whether it is possible to perform any kind of user defined programming in 3DEXPERIENCE.
- An investigation of the 3DEXPERIENCE's environmental impact capabilities.

1.3 Delimitations

The software and corresponding version that was used for simulation in this master thesis was 3DEXPERIENCE Release 2015x On Premise and 3DEXPERIENCE Release 2016x On Premise and On Cloud. The thesis will evaluate applications which are directly related to the *Industrial Engineer* (IEN) and *Manufacturing Engineer* (MEN) roles, within production flow simulation. Product and machine modelling will not be performed, as such is not within the interest of the thesis questions. CAD models will instead be provided by Toyota Material Handling and Prodtex.

2

Frame of Reference

In this chapter, apps and concepts specific to 3DEXPERIENCE are explained, as well as the method of choice for evaluation, and theory relevant to production flow simulation.

2.1 Production flow simulation terminology

The following terms are used throughout the thesis. The terms' explanation serves to avoid reader misunderstandings.

- Source - An operation where the production flow is initiated. The source operation can for example refer to the material arriving at the factory.
- Sink - An operation where the production flow is finalized and the product is consumed.
- Load - A load operation refers to the task of preparing a material, or product, for use. The load operation can refer to an operator initiating a machine by loading it with material.
- Buffer - A buffer is a term referring to a space where products can be stored, to a certain extent. In a factory, a buffer is likely a rack or a shelf where parts are stored while waiting to be used.
- Push flow - A production flow where the operation begin once the required material is available at the station, regardless if the next station has the capacity to make use of the outcome of the first station or not.
- Pull flow - A production flow where the last station in the flow places an order at the preceding station, and that station places an order at the station before it, and so on. In this manner, work stations will only produce if the next station can make use of the outcome.
- Takt time - The time between the outputs of a system. The takt time should be equal to the customer demand.
- Cycle time - The time it takes to complete one full cycle of an operation.
- Capacity - The number of products/part that can be in a process at the same time.
- MBOM - Manufacturing Bill Of Materials is the description of the required parts of a product, and the assembly sequences of those parts.

2.2 3DEXPERIENCE

In 3DEXPERIENCE, the different functionalities offered are separated into *apps*, and in turn, the apps are distributed onto different *roles*. These roles include, for example, *Systems Architecture*, *NC Machining*, *Industrial Engineer* and *Manufacturing Engineer*. This thesis focus on the roles *Industrial Engineer* (IEN) and *Manufacturing Engineer* (MEN) and their respective associated apps. The apps within these roles, which were utilized for creating a functional production flow simulation, are described in detail, whereas the remaining apps within the roles, which are not directly associated with production flow simulation, are listed in subsection 2.2.9. Subsection 4.4.1 through subsection 4.4.3 describes the different apps' relationship to one another, in terms of functionality.

2.2.1 Plant Layout Design

Plant Layout Design is an app available in the *Industrial Engineer* role. It is used primarily to establish a static design of a factory, equipped with geometries of resources such as machinery, products or workers. The *Plant Layout Design* app contains features for transferring details between a 2D blueprint and a 3D representation [15]. This transfer can go both ways as the app contain means for placing 3D geometries and snapping them to the underlying 2D blueprint, as well as creating a footprint of 3D geometries into the 2D blueprint. As this app is focused upon creating a visual representation of a factory, the user do not create geometries in this app but rather place them in the factory, aligning them in regards to the blueprint or other geometries or creating patterns of the same geometry. It is possible to fix geometries to one another, such as a tool to onto a machine or a conveyor to a bin. This is done by assigning *ports* at set points in the resources' geometries. There are different kind of ports for different purposes, such as work piece mount ports, base ports, connector ports. In order to organize factory resources, resources can be assigned to a variety of categories, such as manufacturing cells, robots, workers, transports, conveyors, NC machines etc. These categories stem from the resource's different traits, such as its internal logic; whether it exists in the resource and if it can be programmed; what kind of resources that are aggregated by the resource, as well the kind of reference links available to the resource.

2.2.1.1 Resource definitions

Each type of resource are structured into three different types; *organizational*, *working* and *non-working* resources. Furthermore, the traits of the resources determine whether or not the resource can have internal logic, what type of link that can reference it, what type of resources that is aggregated by it, and what type of resource it aggregates itself. These traits are depicted in Table 2.1.

Table 2.1: Resource categorization chart. Figure reproduced with permission of Dassault Systèmes AB. (Source: Dassault Systèmes [16])

Resource	Category	Logic	Referenced by	Aggregated by	Aggregates
Area 	Organizational	None allowed; non-programmable	A where implement link only	Organizational and Area resources	All types of resources and products
Organizational 	Organizational	Defined in reference only; non-programmable	A where implement link only	Not allowed	All types of resources and products
Robot 	Working	Programmable	A who implement link only	Organizational, Manufacturing Setup, and Area resources	Products only
Worker 	Working	Defined in reference or in context; programmable	A who implement link only	Organizational and Area resources	Products only
Transport 	Working	Programmable	A who implement link only	Organizational, Manufacturing Setup, and Area resources	Products and User-Defined resources
Conveyor 	Working	Non-programmable	A who implement link only	Organizational, Manufacturing Setup, and Area resources	Products only
NC Machine 	Working	Programmable	A who implement link only	NC Machine, Organizational, Manufacturing Setup, and Area resources	Tool Device, NC Machine, and User-Defined resources and products
Industrial Machine 	Working	Non-programmable, no contextual logic is allowed.	A who implement link only	Industrial Machine, Organizational, Manufacturing Setup, and Area resources	Tool Device, NC Machine, and User-Defined resources and products
Inspect 	Working	Programmable	A who implement link only	Organizational, Manufacturing Setup, and Area resources	Tool Device and User-Defined resources and products
Control Device 	Working	Programmable	A who implement link only	Organizational, Manufacturing Setup, and Area resources	User-Defined resources and products
Logic Controller 	Working	Non-programmable	A who implement link only	Organizational, Manufacturing Setup, and Area resources	Products only
Tool Device 	Non-working	Non-programmable	A with implement link only	Tool Device, NC Machine, Industrial Machine, Inspect, Organizational, Manufacturing Setup, and Area resources	Tool Device and User-Defined resources and products
Storage 	Non-working	Programmable	A with implement link only	Organizational, Manufacturing Setup, and Area resources	User-Defined resources and products
Sensor 	Non-working	Non-programmable	A who implement link only	Organizational, Manufacturing Setup, and Area resources	Products only
User-Defined 	Non-working	programmable	A with implement link only	User-Defined, Transport, Storage, Control Device, Tool Device, NC Machine, Inspect, Organizational, Manufacturing Setup, and Area resources	User-Defined resources and products
Manufacturing Setup 	Non-working	Non-programmable	a with implement link only	Organizational and Area resources	All types of resources and products

2.2.2 Equipment Design

Equipment Design is an app available in the *Industrial Engineer* role. The app is used for the creation of mechanical logic and kinematics for resources such as robots, NC machines, conveyors etc. Regarding conveyors, the user can define the type of conveyor, speed, friction, guides, conveyor networks etc. With these parameters defined, the simulation will be more accurate and physical properties is applied

to the simulation. A motion controller is created on a resource reference (Robot, Tool Equipment) or on a resource instance (Robot, Control Device) to control positions, travel limits, safety zones, jog mechanism, tools, speeds, accelerations etc. If several resources are to be programmed within the context of an organizational resource, e.g. a station, a Control Device must be created and then each resource's motion controller is linked to the Control Device. After having set up resources in a proper way, the resources can be used for 3D simulation purposes in *Factory Flow Simulation*.

2.2.3 Factory Flow Simulation

Factory Flow Simulation is an app available in the *Industrial Engineer* role. In the *Factory Flow Simulation* app, it is rendered possible for the user to create a product flow, which in turn can be simulated and the output data analysed. By specifying actions, referred to as activities, to resources the product can be either created, dispatched, buffered, transferred or transformed. For the different resources interacting with the factory flow, data can be manipulated in order to set machine durations, time distributions, delays, quantities, buffer sizes, set product types, behaviours etc. With *Factory Flow Simulation*, one can generate a *Manufactured Item* as well as import data from a planning structure in order to automatically generate a fully functional factory flow. In order to do so, the flow has to be correctly defined with systems and operations in the *Process Planning* app, see subsection 2.2.6. The *Factory Flow Simulation* app contains three variants of visual simulation [15]. These variants are listed in subsection 2.2.3.1 to 2.2.3.3.

2.2.3.1 Discrete Event Simulation

Discrete Event Simulation allows for products to move from one point in the process to another, without having any other resources nor physical conditions taking part. Worker resources are exempted from this, and are animated in this simulation variant. The Discrete Event Simulation variant is used to perform a rough simulation of the system.

2.2.3.2 Dynamic Level 1

The first level of dynamic simulation allows for, besides the functionality mentioned in 2.2.3.1 Discrete Event Simulation, all resources to be animated. In Dynamic simulation, products may be affected by the physics of other products, or resources such as conveyors. This allows for a more accurate depiction as the products risk falling off a conveyor if its incline is too steep or overcrowded by products etc.

2.2.3.3 Dynamic Level 2

With the second level of Dynamic simulation, animations and movements are more sophisticated than in the first level. Resources with programs connected to them will simulate these actions.

2.2.4 Process Flow Simulation

Process Flow Simulation is an app available in the *Industrial Engineer* role. In the *Process Flow Simulation* it is possible to "analyze complex production system with uncertainty and time variability" [15] with DES. The simulated system is structured in a flowchart manner, see Figure 2.1, with representations for general system, transfer system, source system, sink system and buffer system. Within the different system, one can either define corresponding operations, or subsystems. The user defines how the product flows between the different systems, from the raw material in the source to the dispatch of finished products in the sink. The *Process Flow Simulation* app use statistical distributed parameters to handle the variability that exist in the reality. The simulation can be run over multiple cycles with different scenarios to assess the design of the system. The different scenarios can be saved and compared to each other. The user can monitor the state of the system with different charts that are updated during the simulation, see Figure 4.5.

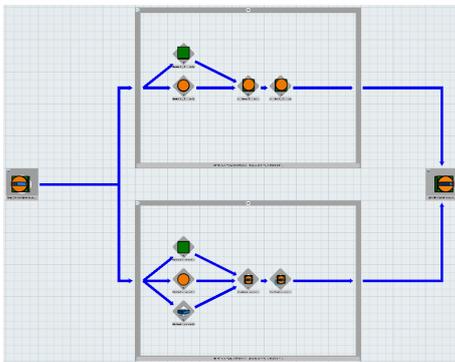


Figure 2.1: Example of *Process Flow Simulation* layout. The flow originate in the source on the left, and flows toward the sink on the right.

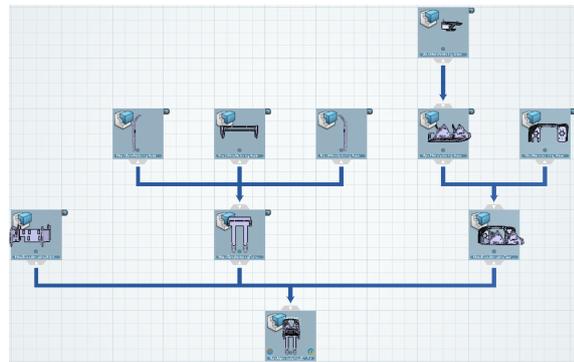


Figure 2.2: Example of a *Manufactured Item* (MBOM) layout, describing how a product should be assembled.

2.2.5 Manufactured Item Definition

Manufactured Item Definition is an app available in the *Manufacturing Engineer* role. In order to connect a product to a process layout, a *Manufactured Item* is required. The *Manufactured Item* is created in the app *Manufactured Item Definition* and consist of a flowchart depicting the procedure in which a product should be assembled (MBOM), see Figure 2.2. Each item in the flowchart is connected to parts or sub-assemblies in a product assembly.

2.2.6 Process Planning

Process Planning is an app available in the *Manufacturing Engineer* role. The app provides tools for defining scope links between *Manufactured Items* and *Process flows*. The systems and operations of a product can be put in order through the use of the *Product flow* command, which is used to describe how the product flows between systems, and the *Precedence link* command, used to describe in which order

operations within a system are allowed to be carried out. It can also be used for balancing *Manufactured Item* and operations between systems.

2.2.7 Equipment Allocation

Equipment Allocation is an app available in the *Manufacturing Engineer* role. The app provides tools for balancing operations on resources, checking resource/system utilization, defining operations, and part positions within a resource.

2.2.8 Planning Structure

Planning Structure is an app available in the *Manufacturing Engineer* role. The app provides tools authoring manufacturing assembly, manufacturing system, product and resource structures. Users can define scope links between manufactured items and products, systems and manufactured items, and resources and systems.

2.2.9 Additional apps

3DEXPERIENCE features additional apps for the *Industrial Engineer* and *Manufacturing Engineer* roles to those explained in section 2.2 and its subsections. These have been excluded as they do not contain any features relevant to the project of production flow simulation at Toyota Material Handling, and has thus not been examined to greater detail. These apps are:

- *Industrial Engineer*
 - Simulation Experience
- *Manufacturing Engineer*
 - Fastened Item Definition
 - Fastener Planning
 - Tool Analysis
 - Work Instructions
 - Time-Motion
 - Assembly Evaluation
 - Assembly Path Optimization
 - Heavy Industry Manufacturing
 - Heavy Industry Process Planning
 - Heavy Industry Structure Fabrication
 - Assembly Definition
 - Assembly Experience
 - Planning Review

2.3 Evaluation of simulation software

There are several different production flow simulation software available on the market. If the appropriate software is chosen, it can then result in improved productivity and reduced manufacturing cost [17]. But if an inadequate software is chosen, it can result in increased cost because of faulty simulation that leads to manufacturing interruptions, among other issues. Therefore there is a need for evaluating a simulation software before purchasing the software.

To provide an objective evaluation and selection of a simulation software, compared to other software or on its own, a structured methodology for the evaluation is required. The selection of a simulation software is also often costly and time consuming and a structured approach should result in a more efficient selection [17]. One common methodology for evaluation is to use a comprehensive list of criteria and use it as a check list to confirm that the software meets the specified requirements [18]. The different criteria can be weighed in accordance to their importance, in aspect to the intended purpose of the software, to be able to provide the software with a final score [19]. If time allows, additional software features could be evaluated, even if they are not currently required as they could be in the future. Alomair et al. [20] presents a brief overview of eight different evaluation methods or techniques that can be found in literature. These are; *"Evaluation criteria, Multi-Criteria Decision Making (MCDM) methods including Analytic Hierarchy Process (AHP), Fuzzy Analytic Hierarchy Process (FAHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Preference Selection Index (PSI), Hierarchical framework, SimSelect, Smart Sim Selector, Scenario, Two-phase evaluation and selection methodology, and Guidelines which can be applied to evaluate simulation tools."* [20]. Some of the methods, such as MCDM, requires that several simulation software are compared to one another, which did not suit this project as it evaluates a single software. Alomair et al. [20] concludes that a list of criteria was the basis for most evaluation methods.

2.3.1 Evaluation framework

Based on the knowledge gained from Alomair et al. [20], the choice was made to adapt the evaluation method developed by Hlupic et al. [18], as it was the most comprehensive method among the methods assessed, while also being applicable to the evaluation of a single software without the need of comparison to other software. The authors of the method, Hlupic et al., has divided the evaluation method into thirteen different categories; General features, Visual aspects, Coding aspects, Efficiency, Modelling assistance, Testability, Software compatibility, Input/output, Experimentation facilities, Statistical facilities, User support, Financial and technical features and Pedigree. Each category includes a comprehensive list with a criteria and classification relation to the subject.

Though Hlupic et al. evaluation framework is dated and lack some essential features of more modern simulation software, it is a good frame of reference to build on. An updated version of Hlupic et al. evaluation framework would suit the project's needs for evaluation of the simulation program.

2.4 Sustainability

This section aims to provide an overview of production flow simulations effect on the sustainability of a production system. It has been divided into the three sub-categories; Social, Environmental, Economic, often referred to as *The three pillars of sustainability*, see Figure 2.3.

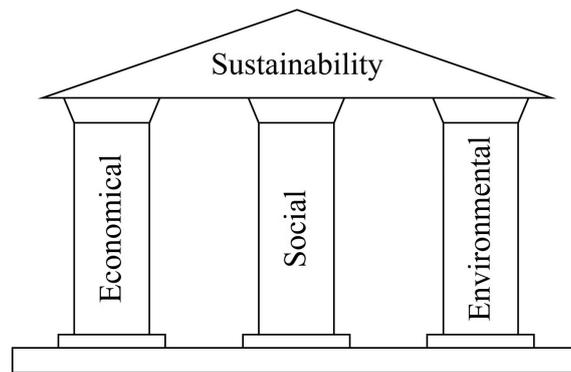


Figure 2.3: The three pillars of sustainability.

2.4.1 Economical sustainability

There are numerous financial advantages with production flow simulation, some which have already been mentioned in this thesis, see section 1.1. One of the most significant advantage is the possibility to, through simulation, test if an investment will be economically sustainable before implementing the investment. Production flow simulation is often used to optimize a system or process to increase the productivity. Simulation can prevent or reduce several of the seven waste activities, *Muda*, described in the Toyota Production System (TPS) [21, Chapter 3]. The increase in productivity and reduction of waste activity leads, not only to the reduction of manufacturing cost per product, but also to a lower environmental impact per product, if the same resources are used.

2.4.2 Social sustainability

Simulation can help with verifying the ergonomic sustainability for workers in a manufacturing context. With simulation software, tasks that are going to be performed by humans can be tested by having a *Digital human model* (DHM) perform the task [22]. The DHM's properties can be changed to represent the different workers e.g. it can be changed to represent the tallest and the shortest worker, respectively, to verify that both are able to reach everything they need in their work. It can also be used to verify that the working position is ergonomically correct. The software can also calculate the different stresses and loads on the DHM while performing the simulated task. This helps the work task designer to design and choose the right tools for the work task and develop a correct standard procedure to minimise the risk of work related injuries, which improves the social sustainability in the work

place. Simulation software can also verify that workers have enough time to perform the assigned tasks and balance the workload between different workers and workstations.

2.4.3 Environmental sustainability

According to a survey by Kiron et al. [23], 67 % of managers believe that sustainability is critical to being competitive in today's marketplace, and 22 % said "*No, but it will in the future*" [23]. Another survey by Cone Communications [24] concludes that 71 % of Americans consider the environment when they purchase goods and 85 % want companies to educate them on how to properly use and dispose of products. This indicates that the environmental aspect is and will be an important concern for companies to be successful in marketing products. A combination between *Life Cycle Assessment* (LCA) and *Discrete Event Simulation* (DES) can provide companies with a more extensive and detailed environmental assessment, which includes dynamic aspects in the system [25], see Figure 2.4 for an image depicting the life cycle thinking. The assessment can be used to eco-label [26] products to show customers that the company's products are environmental friendly, or to show regulators that said products pass the set environmental requirements. A drawback with using simulation for LCA is that it requires extensive data, complex simulation, often long implementation time, verification etc. [27].



Figure 2.4: Life cycle thinking (Source: The National Institute of Standards and Technology (NIST) [28]).

2. Frame of Reference

3

Methods

This chapter describes how the observations of 3DEXPERIENCE and necessary preparations was carried out.

3.1 Observations

In the interest of carrying out a proper evaluation of the 3DEXPERIENCE roles *Industrial Engineer* and *Manufacturing Engineer*, it was vital to thoroughly learn the software in general and the associated apps in particular.

3.1.1 Instructional guides

To familiarize oneself with 3DEXPERIENCE, digital instructional guides (companions) by Dassault Systèmes were utilized. These guides partly served as a gateway to 3DEXPERIENCE where the idea and the structure of the platform was explained, and partly to explain the interface of the specific apps included in the roles *Industrial Engineer* and *Manufacturing Engineer*.

3.1.2 Recreating factory flows

As a sub-task towards the goal of evaluating the *Industrial Engineer* and *Manufacturing Engineer* roles of 3DEXPERIENCE was to simulate parts of the factory flow at Toyota Material Handling, there was a definite requisite of preparing for such a task. One method to attain necessary knowledge for such a task was to construct and simulate other factory flows.

3.1.2.1 Coffee factory

The coffee factory was a factory model previously designed in 3DEXPERIENCE by Dassault Systèmes. The model utilized conveyors, NC machines and manual labour in order to manage the production of three different products, which, at certain points, shared conveyors with one another. Each conveyor contained logic enabling movement in one direction along with guides which are used to define borders. The layout of the factory can be seen in Figure 3.1.

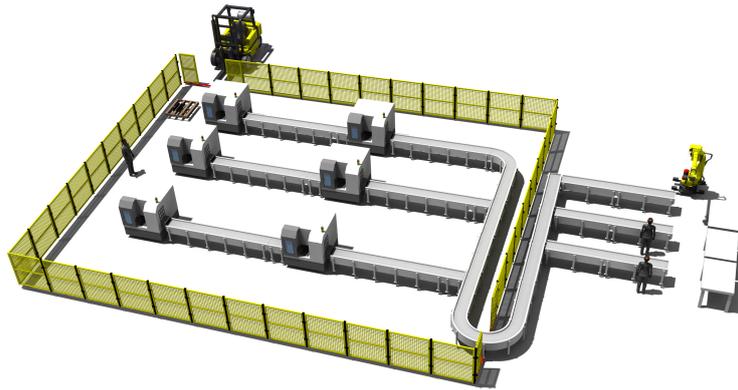


Figure 3.1: Layout of the coffee factory. Figure reproduced with permission of Dassault Systèmes AB.

3.1.2.2 Cup factory

In order to better learn the apps *Plant Layout Design*, *Factory Flow Simulation*, *Equipment Design*, and *Process Flow Simulation*, the production flow of a factory producing Thermos travel mugs was designed and simulated. The task was reused from the course *Simulation of Production Systems* given at Chalmers University of Technology during the fall semester of 2014, where the factory was simulated using AutoMod®. The specific purpose of the exercise was to attain knowledge in the transition between aforementioned apps; such as to find the requirements that *Factory Flow Simulation* puts on the layout which thus has to be designed in *Plant Layout Design*; as well as generating a functional production flow mimicking the cup factory layout.

3.1.2.3 Toyota Material Handling

The final task of simulating a part of the Toyota Material Handling factory in Mjölby was initialized through a meeting with representatives at Toyota Material Handling. A plan was drafted in consensus which provided a guideline for the continuous thesis work. The outcome of this plan can be found in subsection 1.2.1.2.

3.2 Simulation in 3DEXPERIENCE

When working with 3DEXPERIENCE, the main working method consisted of setting up a simulation question or scenario, making a plan how to answer the question or create the scenario, checking which prerequisites were needed and which apps should be used, empirically testing the hypothesis, checking if the outcome was consistent with the original question/scenario, if not go back and redo. In each new app, a scenario of simplistic nature was set-up to test and ensure that the app performed as expected. When this was confirmed, more advance scenarios were tested. Based upon these experiments, it was rendered possible to generate a general work flow for making the different production flow simulations in 3DEXPERIENCE, see subsection 4.4.1 through 4.4.3.

3.3 Evaluation of 3DEXPERIENCE

To evaluate the production flow simulation capabilities of 3DEXPERIENCE, the method described in section 2.3 has been used as a reference point. The method has been updated to suit a more modern production flow simulation software. This update includes both features which were requested of production flow simulation today, but also what can be expected to be included in a production flow simulation software in the near future. Certain criteria included in the framework presented by Hlupic et al. [18] were considered outdated in terms of today's standards in regards of computer software, and were thus omitted. The criteria which were omitted were selected by having the authors of this thesis independently weigh each criteria in order of relevance.

3.4 Data collection

In order to gather the data required to carry out a proper evaluation of 3DEXPERIENCE, regarding to the needs of a large enterprise such as Toyota Material Handling, both written and oral interviews with people at Toyota Material Handling whom the thesis subject concern were carried out. The focus was on performing qualitative data gathering since Toyota Material Handling employs a limited workforce within the subject of production flow simulation. A survey was also carried out where desired simulation software functionalities were rated depending on each other. The survey was carried out with *Google Forms*¹, as this made it possible for the respondents to answer the questions in their own time and it was possible to have additional explanatory text to the questions. A drawback with digital questionnaires is that it is difficult to provide additional explanation to a questions, if needed, so it is of utmost importance that the questions are clear and easy to interpret. Much of the data concerning 3DEXPERIENCE were gathered from the 3DEXPERIENCE's User Assistance [15]. The data was then confirmed empirically with help of the 3DEXPERIENCE software.

¹<https://www.google.com/forms/about/>

4

Results

This chapter conveys the results of both the evaluation of 3DEXPERIENCE and its revision, as well as the outcome of the simulation model.

4.1 Observations

In order to find data of Toyota Material Handling’s demands of production flow simulation software, a survey was used where the respondent, Hoa Hai Gieng at Toyota Material Handling, ranked different general criteria based on their importance in his field of work as a simulation engineer, see Figure 4.1. A higher score indicated a higher importance, with six being most important. The result of the survey shows that the ability to generate environmental data is of the utmost importance for Toyota Material Handling whereas the software price, while still somewhat important, is the least important of the criteria.

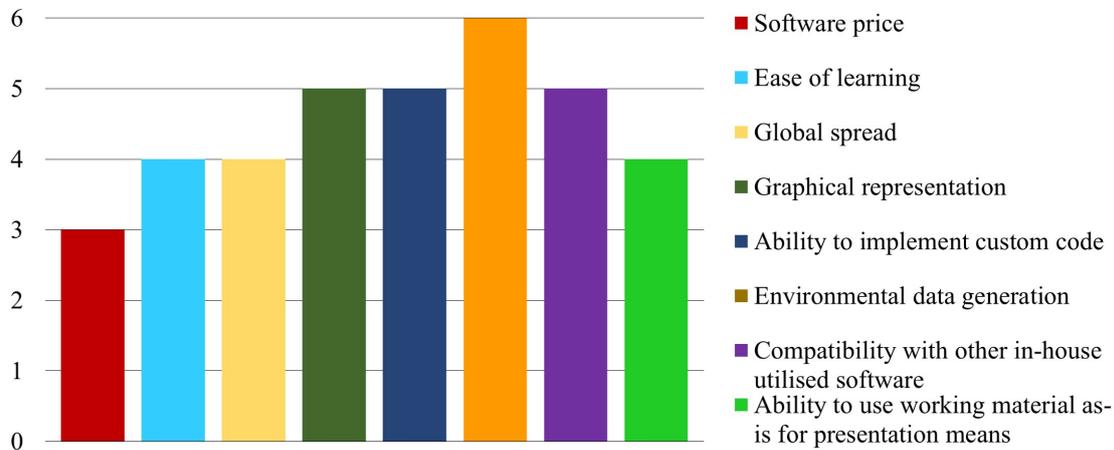


Figure 4.1: The importance of general criteria according to Hoa Hai Gieng.

4.2 Revision of evaluation method

This sub-section presents the final form of the evaluation method and which criteria was omitted, altered or added from the evaluation method. The final evaluation method and results when applied to 3DEXPERIENCE can be viewed in Appendix A.

4.2.1 Omissions

As certain criteria presented by Hlupic et al. [18] represent features that have either turned obsolete or became integrated into a standard in software, these criteria has been taken out in order to avoid redundancy. Other criteria has been taken out as their importance when selecting a simulation software appeared insignificant, based on the result of the weighing of criteria. The result of some criteria were to be considered subjective, thus such identified criteria were taken out of the evaluation method. The omitted criteria can be viewed in Table 4.1 through 4.4.

Table 4.1: Omissions, on the grounds of having *Obsolete criteria*

Criteria	
The length of entity name	Conversion of numbers
Entity name	Printing help text
Limitation on number of displayed icons	Type of menu selection
Number of icons stored in icon library	Writing reports to plotter
Icons with multiple colours	Demo disks
Exit to operating system within the package	Availability of package on standard OS's
Case sensitivity	Availability of package on standard hardware

Table 4.2: Omissions, on the grounds of having *Subjective criteria*

Criteria	
Ease of icon development	Precision of added code
Ease of using screen editor	Comprehensiveness of added code
Readability of added code	Quality of on-line help
Ease of conceptualisation of simulation logic	Ease of learning
Ease of using	Readability of source code
Ease of model editing	Quality of prompting
Quality of facility for documentation notes	Quality of error messages
Ease of debugging	Quality of output reports
Understandability of output reports	Quality of experimental design facility
Quality of data analysis facility	Quality of documentation
Quality of the support for programming concepts	Quality of data storage, retrieval and manipulation facilities
Ease of installation	

Table 4.3: Omissions, on the grounds of having *Standardized criteria*

Criteria	
Formal logic	Virtual screen
Run-time applications	Undo/redo commands
Specification of time units	Use of mouse
Specification of length measures	On-line help
Resizing of icons	Search facilities within help
Rotating of icons	Number of different random number streams
Switching between screens	Antithetic sampling
Print screen facility	Virtual memory facility

Table 4.4: Omissions, on the grounds of having *Irrelevant criteria*

Criteria	
Types of icons	Audible alarms
Merging icon files	Duration of training courses
Change of icons during simulation	Frequency of training courses
Type of time variable	User group meetings
Length of the lines in coding editor	Frequency of user group meetings
Text editor as integral part of the package	Installation costs

4.2.2 Alterations

Certain criteria were changed in different ways. Some criteria were changed in order to have them better suit the current needs of the evaluation method, whereas other criteria were incorporated into other to avoid redundancy in an effort to reducing the size of the questionnaire without compromising the comprehensiveness of the method. The following criteria has been altered:

- *Versions of software for different operating systems* - As operating system manufacturers nowadays, in general terms, provide free version updates of their operating system, the point of interest is not which version of the operating system which is supported by the software, but rather which type of system. The possible answers has therefore been changed accordingly.
- *Formal education in simulation required for software use* - This criterion has been integrated with a more general criterion.
- *Changing the colour of the element status display* - This criterion has been integrated with a more general criterion.
- *Writing reports to printer* - The feature of printing is located in the operating system itself, not in the software. However, software may adjust the material which is to be printed, so that it fits the user's needs in a better way. The criterion was therefore changed.
- *Custom tailored training course* - Merged into an answer to another criterion.
- *Interaction* - As the criterion was ambiguous, it was clarified to avoid misunderstandings.

- *Educational discount* - Merged with quantity discount into a criterion handling all discounts.
- *Quantity discount* - Merged with educational discount into a criterion handling all discounts.

4.2.3 Additions

Based upon the input of representatives at Toyota Material Handling and the strive for operating responsibly in today's society, the categories *Presentation material generation* and *Environmental consciousness* were added to the existing method developed by Hlupic et al. [18]. The criterion evaluating the possibility of point-cloud data mapping was added to the modelling assistance category, and the criterion for online dependency requirement was added to the financial and technical features category.

4.2.3.1 Presentation material generation

The purpose of the *Presentation material generation* category is to evaluate whether or not the software provides means that allow for a quick and effortless transition between the work object in the development model and how said model is presented. As mentioned by Toyota Material Handling simulation engineer and interviewee, Hoa Hai Gieng, a main purpose of simulation at Toyota Material Handling is to determine whether or not an investment should be carried out. While there are tools currently in use by Toyota Material Handling which to some extent satisfy their simulation needs, there is a potential to make the transition between working material and presentable material seamless. This would potentially enable the working material to be able to be used as-is during presentation dedicated to personnel which has limited to no knowledge of traditional production flow simulation.

The category includes evaluation criteria such as the level of graphics in the development model; high-quality graphics in the development model could allow for the same graphics to be used in the presentation model. It also evaluates the software's ability to display comprehensible and high-quality data and graphs as well as the creation of videos for demonstration purposes. If these functions are integrated into the software in a satisfactory fashion, that would eliminate the need for third party software to achieve the same result. This in turn has the potential to save both time and money for the user.

4.2.3.2 Environmental consciousness

In combination with the ever-increasing awareness of environmental issues in today's society, both from the producer's and the customer's point of view, see subsection 2.4.3, along with the lack of coverage of these issues in the evaluation method presented by Hlupic et al. [18], there was an imminent need to try to cover said issues. Allowing for environmental analysis capabilities of software to be factored into the evaluation may affect companies to gain a natural positive stance towards making decisions in their every-day routine based upon the environmental impact of the decisions, as these data can be easily accessible. These decisions in turn may

affect the customers' and/or governments' opinion of the company [29], which can give the company a competitive advantage.

The category *Environmental consciousness* contain criteria which are used to evaluate if the software has the capability to assist in the construction of a *Life Cycle Assessment* (LCA) of the product, and how comprehensive such an analysis would be. It also features criteria regarding with which units environmental impact is measured and the customizability of the units. A criterion which is used to evaluate the possibility of converting the generated environmental data into comparable monetary data exists. Such a feature would most likely have great value for managers with low expertise regarding environmental impact of products and production.

4.2.4 Revised evaluation method

The revised version of the original evaluation method, developed by Hlupic et al. [18], can be found in its entirety in Appendix A. It is divided into 15 categories with a varying number of criteria in each category. Each criterion has two or more possible responses to describe the evaluated criterion's functionality. These are noted in the *Classification* column, whereas the criteria are found in the *Criteria* column. For the method itself, disregard that certain responses are found in bold text, see section 4.3 for further information.

4.3 Evaluation

The outcome of the evaluation, that is, how 3DEXPERIENCE fared in each of the criteria, can be seen through the functionalities' bold font in Appendix A. In order to make it easier to grasp the result of the evaluation, a real number between 0 and 1 was appointed to each criterion based on how well 3DEXPERIENCE fared, with a 0 being awarded in cases where 3DEXPERIENCE fared badly and 1 where it fared well. For criteria where 3DEXPERIENCE fared decently, an intermediate score was awarded. The score from each criterion in each category was then tallied and divided by the number of criteria in the corresponding category so that a radar chart could be utilized to showcase the outcome, see Figure 4.2. 3DEXPERIENCE excels in user support, visual aspects and modelling assistance, but also comes off very well in a number of categories. However, 3DEXPERIENCE lacks in statistical facilities, financial and technical features and, in particular, environmental consciousness. It should be noted though that as the each category had a varying amount of criteria, categories with fewer criteria has a higher impact per criterion on its category's representation in Figure 4.2.

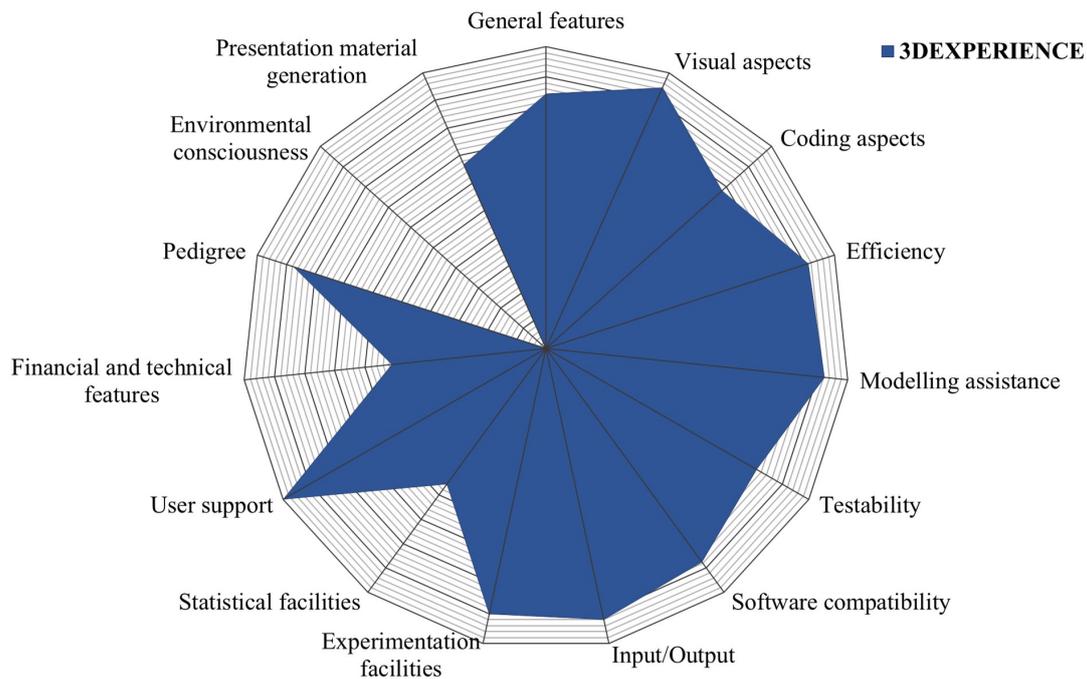


Figure 4.2: Evaluation of 3DEXPERIENCE per category. The more area filled, the better the corresponding category fared in the evaluation.

4.4 3DEXPERIENCE

During the period of this thesis work, 3DEXPERIENCE demonstration servers has been used to store data. This means that it was impossible to export or transfer any data created on a demonstration server. The effect of this was that all models created in 3DEXPERIENCE 2015x could not be transferred to 3DEXPERIENCE 2016x, and vice versa, as these software versions were running on different demonstration servers. This has led to that the main results from the experiments, see section 3.2, are the work flows described in subsection 4.4.1 through 4.4.3, and the ability to answer the different criteria questions in the evaluation. Different simulations' process steps that are of interest has been documented through videos where Toyota Material Handling's products, flows and layout were used. The purpose of these videos were to show the simulation possibilities of 3DEXPERIENCE with a production flow that Toyota Material Handling are already familiar with.

4.4.1 Creating a *Factory Flow Simulation*

This subsection describes the general working procedure for creating a *Factory Flow Simulation* in 3DEXPERIENCE in a chronological list, to provide a better understanding of the process. In Figure 4.4, the work-flow for creating a *Factory Flow Simulation* based on the viewpoint of app usage.

1. Create or modify 3D-representations for all objects in the production system.

- 3DEXPERIENCE has several 3D-modelling apps such as *Part Design*¹.
2. Create the production system layout in the app *Plant Layout Design*. The layout can be created from an existing 2D-layout by putting the 3D-representations on the 2D-layout.
 3. Define logic for resources in the app *Equipment Design*.
 4. Define the flow of products in the system with the app *Factory Flow Simulation*. (Can be generated from *Process Planning* data. See subsection 4.4.3)
 5. Simulate the system in *Factory Flow Simulation*. Verify that the system runs as intended, otherwise go back and revise.
 6. Create different manufacturing scenarios to test the system.

4.4.2 Creating a *Process Flow Simulation*

This subsection describes the general working sequence for creating a *Process Flow Simulation* in 3DEXPERIENCE in a chronological list, to provide a better understanding of the process.

1. Create 3D-representations for all products. 3DEXPERIENCE has several 3D-modelling apps such as *Part Design*¹.
2. Create *Manufactured Item* (MBOM) for the products in the *Manufactured Item Definition* app. Scope the *Manufactured Item* to a Physical Product. Define the assembly order in *Manufactured Item* by drag and drop of components from the Physical Product.
3. Define the manufacturing scope in *Process Planning*.
4. Create a process flow in *Process Planning* with all the operations and connect the steps in the *Manufactured Item* to the corresponding operations, or drag and drop steps from the *Manufactured Item* to create operations automatically.
5. Define cycle times, capacities, MTBF, MTTR, precedence links, shift model, production demand etc.
6. Simulate the process in *Process Flow Simulation*. Verify that the system runs as intended, otherwise go back and revise.
7. Create different simulation scenarios to test the system.



Figure 4.3: Work-flows for creating a *Process Flow Simulation* from an app perspective

¹A CATIA app in 3DEXPERIENCE.

4.4.3 Creating a *Factory Flow Simulation* using *Process Planning* data

This subsection describes the general working sequence for creating a *Factory Flow Simulation* from *Process Planning* in 3DEXPERIENCE in a chronological list, to provide a better understanding of the process. Figure 4.4 depicts the work-flow for creating a *Factory Flow Simulation* based on *Process Planning*, from the viewpoint of app usage.

1. Follow steps 1 to 5 in subsection 4.4.2.
2. Follow steps 2 to 3 in subsection 4.4.1.
3. Assign the *Manufactured Item* parts to the operations, and operations to the resources in the 3D layout with the Assignments Manager in the *Planning Structure* app.
4. Define the operation position within the resource in the *Equipment Allocation* app.
5. In the *Factory Flow Simulation* app, select *Synchronize with Planning Data* to generate a *Manufacturing Product*. Select *Generate data model from process planning* and a *Factory Flow* is generated.
6. Follow steps 5 to 6 in subsection 4.4.1.

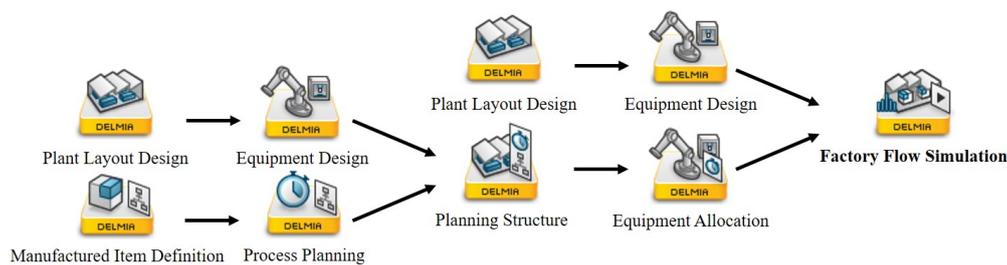


Figure 4.4: Two different work-flows for creating a *Factory Flow Simulation* from an app perspective. One based on subsection 4.4.1 and one based on subsection 4.4.3.

4.4.4 Simulation model

Due to software shortcomings (see subsection 5.1.2, generating a more advanced flow in the *Factory Flow Simulation* app was, during the duration of the thesis project, impossible. This caused the main focus to shift to simulate the desired part of Toyota Material Handling's production flow in *Process Flow Simulation*. The main problem in *Factory Flow Simulation* for Toyota Material Handling's flow was that it was not possible to assign operations to robot resources. Robots could only be assigned to perform transfer task or assigned to another resource. As the desired part of Toyota Material Handling's flow consist mainly of different robot-cells, *Factory Flow Simulation* was not yet ideal for that part of the factory. It should be mentioned though, that 3DEXPERIENCE' *Factory Flow Simulation* worked splendidly for simulating assembly and machining operations with DHM's. Thus if a simple visual flow was desired the, *Factory Flow Simulation* would be the simulation app

to utilize in the matter.

The possibility of generating an automatic flow in *Factory Flow Simulation* from a *Process Planning* validates the work of making all the planning steps, see subsection 4.4.3, before doing a *Factory Flow Simulation*. In the case of Toyota Material Handling's flow where the *Factory Flow Simulation* app still is not ready for their advanced flow, the company would be able to perform all the planning steps and simulate what their desired output in the *Process Flow Simulation* app. At a later point in time, when the *Factory Flow Simulation* app is updated to handle all the features needed for Toyota Material Handling's flow, the company can do a more advanced visual simulation in *Factory Flow Simulation*. Noteworthy is that the visual simulation of robot-cells can be done in the *Robot Simulation* app under the *Robotics Simulation Engineer* role. However, when several robot-cells and other resources are combined and a production flow is desired, the *Factory Flow Simulation* app is required.

4.4.5 *Process Flow Simulation* model

During the project, a detailed *Process Flow Simulation* of the first station in the desired flow at Toyota Material Handling was designed, in order to validate the capabilities of *Process Flow Simulation*. The simulation model includes the creation of two different *Manufactured Items*, and a process flow constructed in *Process Planning*. Simulation in *Process Flow Simulation* was performed, see Figure 4.5, as a simulation example to validate that the system performed as intended with different production modes, such as push or pull mode. Scenarios were tested where different demands and supply of the products and parts were used. Simulation validation of such scenarios were performed by comparing the expected output with the actual output, and the result was that 3DEXPERIENCE did perform as expected in this regard. Note that no actual production data from Toyota Material Handling, e.g. cycle times, distributions etc., has been used during the simulations.

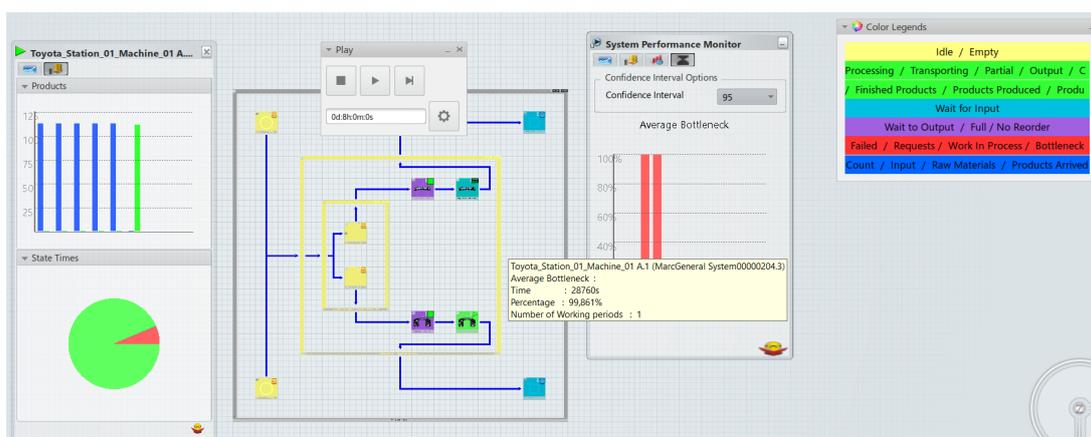


Figure 4.5: Example of *Process Flow Simulation* for Toyota Material Handling's first welding station.

The first welding station at Toyota Material Handling consisted of a storage where

parts were picked and kitted by an operator. The parts were placed in a manipulator with two fixtures, one on which two robots performed welding, and one that could be loaded during the welding of the first fixture. A 3D-model of the robot-cell is depicted in Figure 4.6. When the first two robots were finished, a third robot, the handling robot, picked up the part from the fixture and transferred it to the next pair of robots so that the robots could continue to weld the part while the handling robot held the part. This procedure is known as jig-less welding. After the handling robot had removed the part, the manipulator performed a swivel motion and exchanged the fixtures so that the loaded fixture went in to the robot cell and the empty one went out to be loaded once more. When the second pair of robots were finished with their welding, the handling robot placed the product on a conveyor belt which brought it out from the robot cell.

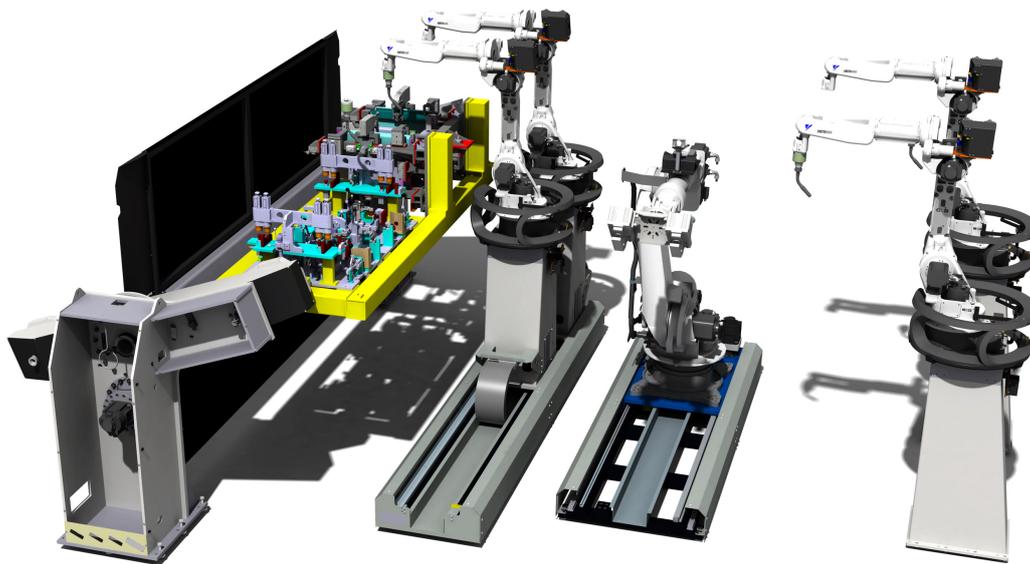


Figure 4.6: CAD model of robot-cell at Toyota Material Handling.

Based on experience and the knowledge of the Toyota Material Handling welding line, the *Manufactured Item*, representing the MBOM, was constructed to resemble the real assembly sequence as close as possible for the first welding station, see Figure 4.8. In the welding station, two different pallet trucks' rear bumpers, see Figure 4.7, were to be assembled. As the objective of this thesis was to evaluate 3DEXPERIENCE, and not the Toyota Material Handling production line, there was no need to construct the *Manufactured Item* as an exact mirror image of the real MBOM.

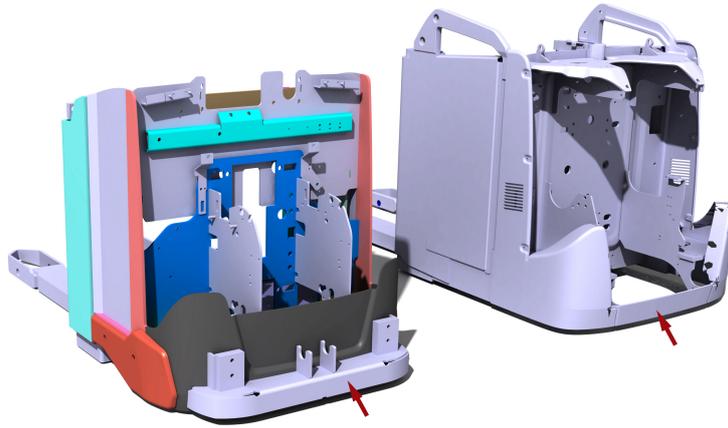


Figure 4.7: Pallet trucks, the arrows highlight the bumpers assembled in the first station.

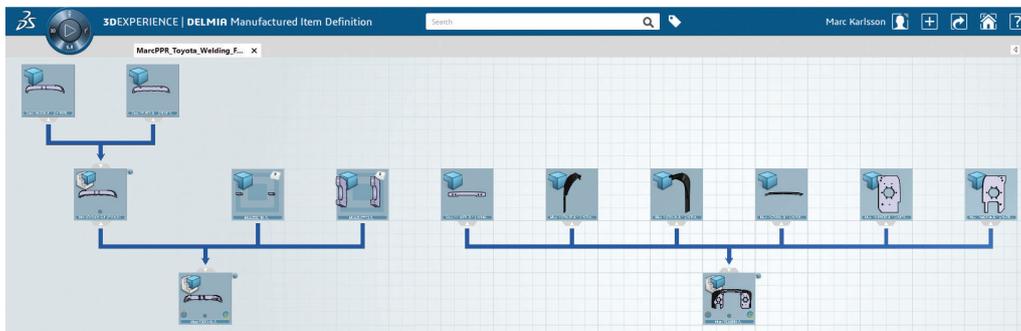


Figure 4.8: The *Manufactured Item* for the first welding station.

The source system used *create* activities for each different product needed, in order to create them. The supply of products were defined with *Define operation* manager. The inter-arrival time, proportion and lot size were set in the manager, see Figure 4.9. The supply was defined in *Production Supply Definition* manager when running simulations with the option "*Enable Automatic Creation of Sources & Sinks*", see Figure 4.12.

Define Operations					
Operation	Outputs	Inter-arrival Time	Proportion	Lot Size	
Source_249835 A.1 (249835)	249835.1	Constant(3600)	1	30	
Source_250411 A.1 (250411)	250411.1	Constant(3600)	1	30	
Source_247773_1 A.1 (247773.1)	247773.1	Constant(3600)	1	30	
Source_247773_2 A.1 (247773.2)	247773.2	Constant(3600)	1	30	
Source_252181_1 A.1 (252181.1)	252181.1	Constant(3600)	1	30	
Source_252181_2 A.1 (252181.2)	252181.2	Constant(3600)	1	30	

Figure 4.9: *Define Operations* for source system, *Process Flow Simulation*.

General systems were created to represent different processes in the station, e.g. loading, unloading, general operations etc. Within the general systems, correspond-

4. Results

ing operations were created. For example, the manual loading of the fixture that holds the parts for the first pair of welding robots was represented with a general system with load operations for each part, see Figure 4.10. The general systems were then connected to a buffer system.

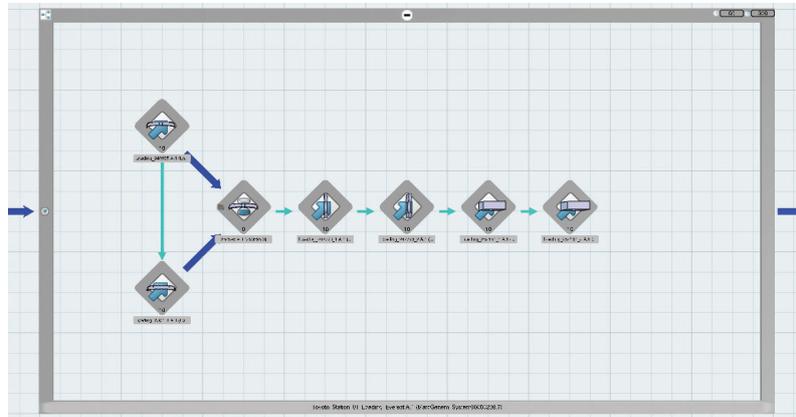


Figure 4.10: General system with loading operations in *Process Flow Simulation*.

The buffer had a capacity of 1 and a reordering point of 0. The buffer represented the loaded fixture and was allowed to send the loaded products to the welding system, a general system with general operations, when it was available. When the buffer was empty, it sent an order to the loading system that it was ready to receive more products.

The sink system contained operations for each desired end-product. The system used pull strategy, which meant that the sink system placed the orders at previous systems, see section 2.1. This was done at set intervals to resemble a takt time. When running simulations with "*Enable Automatic Creation of Sources & Sinks*" the demand was set with the *Production Demand Definition* manager, see Figure 4.11.

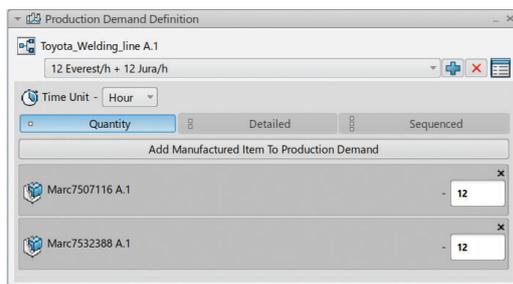


Figure 4.11: *Production Demand Definition* manager.

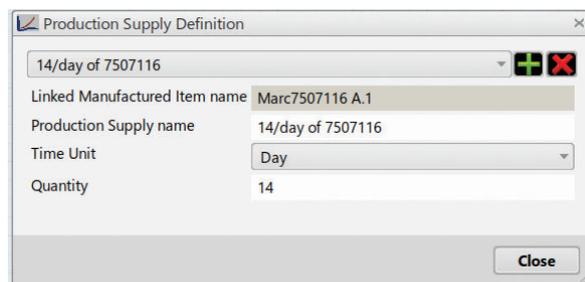


Figure 4.12: *Production Supply Definition* manager.

When developing the model for the welding station, some key tools and elements were observed. 3DEXPERIENCE has a set of functions called *B.I. Essentials* which are able to display relevant information and key figures in the different apps, e.g. link analysis, assignment status, utilization, revision status, system update status, operation placement status etc. These features were helpful when checking that

all parts were implemented correctly. When creating the flow, a key aspect was to check that each operation had the right input and output. This was performed with the *Define operation manager*, and with the *Assignment manager*, the correct *Manufactured Items* were assigned to their corresponding operations. Another useful tool was the *Manufacturing System Gantt*, accessed from the *Process Planning* app. With the *Manufacturing System Gantt*, the user could observe the precedence of the operations, the length of the operations, the takt time of the system etc.

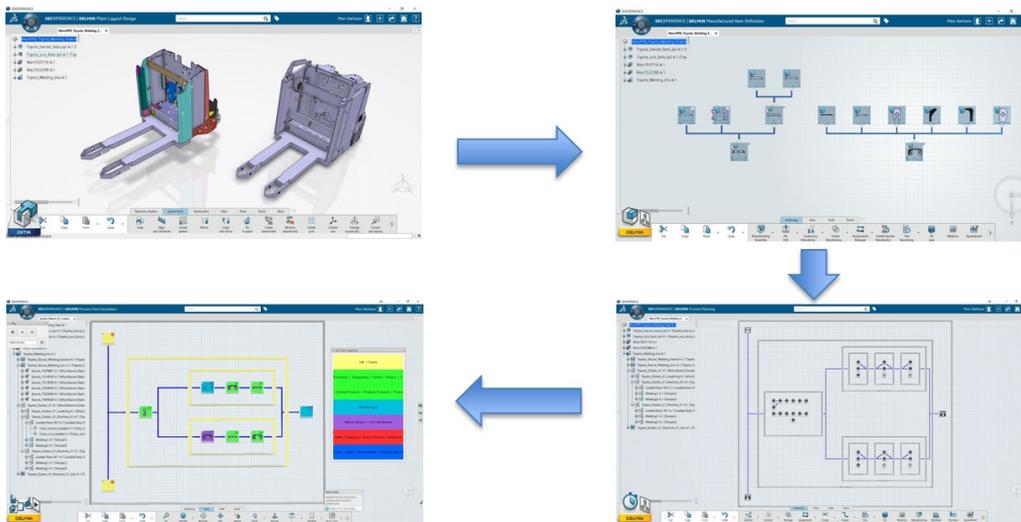


Figure 4.13: Work-flow for creating the *Process Flow Simulation* model of Toyota Material Handling's welding cell.

5

Discussion

This chapter provides a discussion of 3DEXPERIENCE in general and its applicability at Toyota Material Handling, as well as of the evaluation and its method.

5.1 3DEXPERIENCE

This section provides a critical approach to issues related to the software 3DEXPERIENCE, and its potential implementation at a large enterprise for the means of production flow simulation.

5.1.1 Transition

Depending on the earlier simulation software used, along with personal experience, the ease of transition into using 3DEXPERIENCE as the primary production flow simulation software can vary. Transitioning from a more traditional simulation software, where the user has to write the simulation program in a programming language, to 3DEXPERIENCE's more graphical programming design where, today, most programming is done by mouse clicks and pre-defined functions can be a difficult transition. The main advantages of using 3DEXPERIENCE for production flow simulation are its PLM capabilities and good integration with other apps within 3DEXPERIENCE and other software from Dassault Systèmes. If the user is familiar to other Dassault Systèmes applications such as CATIA®, DELMIA®, SOLIDWORKS®, SIMULIA® etc., then many functions and basic working sequences will most likely appear familiar. It is also advantageous if the user already uses 3DEXPERIENCE for other purposes, such as CAD design, robot programming etc., as the user already know the basic concept of 3DEXPERIENCE and the user can easily utilize the objects created in other apps in 3DEXPERIENCE for simulation purposes.

5.1.2 Encountered issues

A number of issues with the 3DEXPERIENCE software has been experienced during the thesis work. One of the issues was that the software was experienced as slow running, it took a long time to open files, save files, switching between apps in 3DEXPERIENCE etc. Another issue was that the software shut-down because it encountered an unidentified problem. This often occurred when the program had a high workload such as when multiple models were open, when opening a large model

etc. It is hard to say if it was the software's fault that it was unstable or if it was the hardware which was to blame. There are some indication that the hardware used for the thesis work did not meet the requirements, such as the graphics card not being fully supported by 3DEXPERIENCE. Although, 3DEXPERIENCE never used the full capacity of neither CPU nor GPU when under high workload which contradict that it was the hardware that was the problem. Another possible explanation could be that the issues occur due to poor connectivity between the local workstation and the host server. However, regardless of reason, this problem reduced the overall user experience of 3DEXPERIENCE and required time that could have been used for value adding activities. Certain functions within the *Industrial Engineer* and *Manufacturing Engineer* roles were not functioning as intended. The ability to generating a factory flow simulation based on process planning data, as described in subsection 4.4.3, had a tendency of failing without delivering a proper error message, describing the error. Furthermore, situations has occurred where generating a factory flow initially fails, after which 3DEXPERIENCE was restarted and the same function was then called upon with greater success, without any changes having been made. This indicates that the software was not deterministic in its output. Some of the apps' functions, e.g. menus, buttons, and dialogue boxes, were not working as intended, due to the function being present in several apps, but were not implemented in each of these apps. E.g., in *Process Flow Simulation* the Context menu for the *Manufactured Item* had a *Resulting Product* function but lacked options, see Figure 5.1. However, in *Manufactured Item Definition*, the *Resulting Product* had options and functioned as intended, see Figure 5.2.

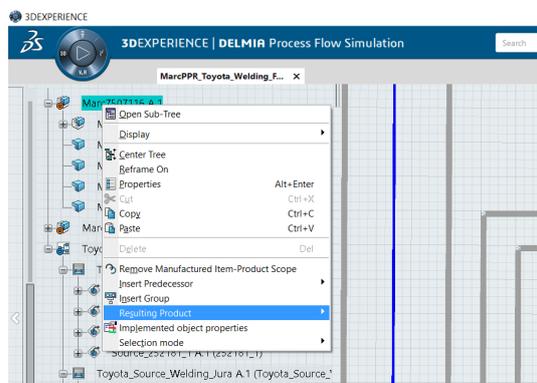


Figure 5.1: Example of missing options for Resulting Product in context menu, *Process Flow Simulation* app.

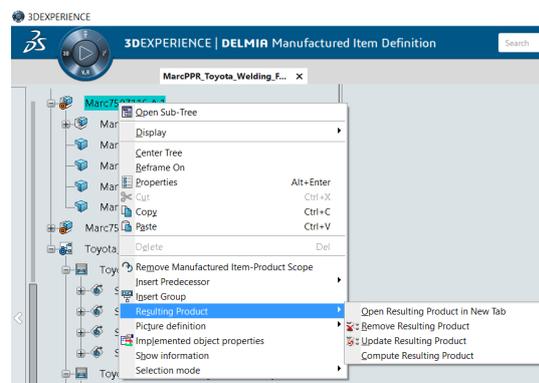


Figure 5.2: Example of the correct options for Resulting Product in context menu, *Manufactured Item Definition* app.

5.1.3 Toyota Material Handling

One of the thesis' research questions, see subsection 1.2.1.1, was "*Is 3DEXPERIENCE suitable for large enterprises?*". In this thesis, Toyota Material Handling served as representative of large enterprises. For further discussion of the matter, see subsection 5.3.2.1.

As Toyota Material Handling uses several of Dassault Systèmes earlier standalone

software, CATIA[®], DELMIA[®], ABAQUS¹ and they use 3DEXPERIENCE for *Robot Arc Welding Programming*, a migration to use the same apps in 3DEXPERIENCE would be favourable. By doing so, Toyota Material Handling could utilize the full extent of 3DEXPERIENCE's PLM and collaboration capabilities. A reduction of the risk of doing the similar operations in different software for the same end, thus saving time and money, would be acquired. Although the migration from QUEST to production flow simulation in 3DEXPERIENCE will most likely be a cumbersome process, as there are large differences between the software. QUEST is a programming based software whereas 3DEXPERIENCE is graphical based. Therefore, a low amount of knowledge and data can be transferred from QUEST to 3DEXPERIENCE.

5.1.4 Development of 3DEXPERIENCE

The thesis project has utilized both 3DEXPERIENCE 2015x On Premise, 3DEXPERIENCE Release 2016x On Premise and On Cloud. Distinct changes between the versions has been detected, which has given the impression that Dassault Systèmes are updating and improving the 3DEXPERIENCE software. With the On Cloud version of the software, it is possible for Dassault Systèmes to automatically install software updates which will ensure that the user always has the latest version. Overall it seems that Dassault Systèmes is aware of which functions that are lacking support in terms of production flow simulation, and has a plan of how and when to implement these functions. An indication of this is that Dassault Systèmes has yet to implement all necessary features required for advanced production flow simulation, but has rather implemented basic features and ensured their functionality. This allows for a solid foundation upon which more advanced functions can be based.

5.1.4.1 *Factory Flow Simulation*

The *Factory Flow Simulation* app in 3DEXPERIENCE is excellent for visual display and to test a factory flow. Although the app is missing some features for more advanced simulation, e.g. handling different products in the same machine, production demand, shift schedule, handling of AGVs/forklifts/monorails, collision avoidance, etc. Noteworthy is that with the 2016x release of 3DEXPERIENCE, the following features were added compared to the 2015x release: Power and Free conveyors, Load & Unload activities, Conveyor Decision Zones, Pull mode, Time distribution, Failure & Repair, Bottleneck analysis, among others. This progress confirms that the simulation apps are continuously updated, which in turn opens up for 3DEXPERIENCE to be further evaluated in the future.

5.2 Evaluation

The evaluation method, originally developed by Hlupic et al. [18], which was the basis of the method used in this thesis, was certainly comprehensive and covered

¹Acquired by Dassault Systèmes 2005 and since incorporated in SIMLIA [30]

many different areas and aspects which a simulation software is expected to include. However, it had left out certain areas, such as environmental consciousness, and instead went into meticulous detail in other areas. The absence of an environmental consciousness category in the original method, while odd by today's standards, probably has the explanation in the fact that the model dates back to 1999. While environmental consciousness was certainly an issue in 1999 as well, it is less likely that it had yet made the connection to simulation software just yet. This assumption is supported by the fact that 3DEXPERIENCE lacks such functionality as well. However, Toyota Material Handling's interest in extracting environmental data from their simulations shows that there is a definite customer demand for it.

5.2.1 Sustainability

As described in section 2.4, the three pillars of sustainability are the economic, the social and the environmental pillars. In the revised evaluation method, the *environmental consciousness* covers the third pillar, and the economic pillar is subtly covered throughout the entire evaluation, as the essence of production flow simulation is about finding a more sustainable production system by using a tool which does not put your actual system at risk. In the case of the social sustainability, while 3DEXPERIENCE do offer comprehensive evaluation of ergonomic work positions, the apps used to perform such evaluations are not included in neither the *Industrial Engineer* nor *Manufacturing Engineer* roles. However, while there is no app or function within the scope of the thesis which is solely dedicated to social sustainability evaluation, *Industrial Engineer* and *Manufacturing Engineer* do offer the possibility of balancing work stations, which in turn can be manned by operators. Such features can be used to improve the work task distribution more evenly, which can lead to an increased satisfactory rate among the operators, and thus increased social sustainability in the work place.

5.3 Methods and results

This section serves to convey a critical discussion of the methods used, and the outcomes, of this thesis.

5.3.1 Data collection

The main source of data collected for the evaluation of the production flow simulation capabilities of 3DEXPERIENCE were based upon the thesis authors' own experiences with the *Industrial Engineer* and *Manufacturing Engineer* roles. Therefore, certain criteria may have been evaluated erroneously. In the comparison between the evaluation's outcome and the needs of Toyota Material Handling, one has to account for the fact that the importance of general criteria at Toyota Material Handling is based on the input of merely one person. While having a survey result based on a single input can certainly be interpreted as misrepresentative of the cause, one can also consider it as having a 100 % response rate of the people affected by the possible

software change, as the respondent is the sole engineer working with simulation at Toyota Material Handling.

5.3.2 Evaluation of 3DEXPERIENCE

In efforts of keeping the evaluation method as neutral and objective as possible, certain criteria were removed which were deemed to be too subjective. However, certain criteria which had a similar structure to the removed criteria were kept in the evaluation method, as omitting or changing them would cause more harm than benefit to the method. This rendered the revised method to have a slightly skewed representation in the effort of objectiveness. Furthermore, as 3DEXPERIENCE is the only production flow simulation software which has been evaluated in the thesis, there is a lack of frame of reference for the outcome of the evaluation, as it is not being compared. Comparing it to QUEST would have been an option, but doing so would have not fit the time frame put in place for the thesis, as yet another software would have had to be thoroughly learned in order to be evaluated.

5.3.2.1 Representativeness of Toyota Material Handling

As the evaluation method has been revised based partly on industrial input from Toyota Material Handling, the matter of the representativeness of Toyota Material Handling as a reference for companies using simulation software is required to be discussed. While the base method, developed by Hlupic et al. [18], is intended to be applicable for both educational and industrial use, the same cannot be said with certainty for the revised version. This is due to the nature of the references upon which the revisions are based. Toyota Material Handling has 1 850 employees at their Mjölby factory [13] and is thus to be considered a large enterprise. Therefore, while it is possible that the revised method is indeed applicable by other user groups besides large enterprises, this has not been evaluated in this thesis.

6

Conclusion

In this chapter, the findings of the thesis are put into perspective in regard of research questions and methods used, and a stance of the outcome is presented.

6.1 Evaluation of 3DEXPERIENCE

The result of the evaluation is equivocal. To one part, 3DEXPERIENCE is deemed exceptionally suitable for a large enterprise such as Toyota Material Handling as it performed well in the visual aspects, coding aspects and software compatibility; categories which were all ranked as important by Toyota Material Handling. One of the cornerstones of 3DEXPERIENCE is its holistic take on PLM, which 3DEXPERIENCE executes well. This comes off in a great way both in function and in demand of Toyota Material Handling, as they valued the importance of compatibility with other in-house utilised software to five out of six. As 3DEXPERIENCE allows for such a variety in functionality, it is likely to fit most of the functions at the company. However, the most sought-after features in simulation software, environmental consciousness, received a zero in its evaluation. 3DEXPERIENCE's ability to visualize statistical data is, in itself, at a basic level. While this may be sufficient, if it is not, then the data can easily be exported and later used in software more dedicated to statistical representation. Thus, 3DEXPERIENCE's meagre performance in the statistical facilities category may be compensated in such a way, even though it is not an optimal solution and contradicts the essence of 3DEXPERIENCE.

6.2 Simulation model

The thesis concludes that *Process Flow Simulation* in 3DEXPERIENCE is suitable for the simulation needs of a large enterprise such as Toyota Material Handling. However, the *Factory Flow Simulation* app does not yet have all the functionality Toyota Material Handling requires for simulation of their production flow on a more visual level. There are, however, apps in the 3DEXPERIENCE software that are able to display parts of the production process visually, e.g. the visualisation of robot-cells can be done in *Robot Simulation*.

6.3 Research questions

This section contemplates the research questions stated in subsubsection 1.2.1.1. The first research question addressed the possibility of evaluating 3DEXPERIENCE. Due to set delimitations, only the *Industrial Engineer* and *Manufacturing Engineer* roles have been evaluated, and not 3DEXPERIENCE in its entirety. However, it was still possible to evaluate the software within the set boundaries. Previous research in the subject of production flow simulation software evaluation is scarce, which led to the utilization of an albeit comprehensive but aged evaluation method. The outcome of the evaluation method, after having been revised to better fit with the nowadays demands, was a thorough analysis of the mentioned roles and their functionalities, where 3DEXPERIENCE fares splendidly in categories such as visual aspects, user support and modelling assistance, but falls short in statistical facilities, financial and technical features and, in particular, environmental consciousness.

In regards of the second research question, while 3DEXPERIENCE matches the current simulation needs of a large enterprise such as Toyota Material Handling to a broad extent, one needs to take into consideration if there are other production flow simulation software that matches such a demand just as well as 3DEXPERIENCE, but which fares better in environmental sustainability aspects, as environmental consciousness was ranked as the top priority of simulation software features by Toyota Material Handling.

Concerning the third research question, as has been mentioned regarding the outcome of the evaluation, 3DEXPERIENCE does not currently support the demand of sustainability features in large enterprises such as Toyota Material Handling.

6.4 Future research opportunities

Due to the scarce and aged research in the subject of production flow simulation software evaluation for single-software evaluation, there is a vast opportunity to continue the research carried out by Hlupic et al. [18] and continued by the efforts in this thesis. If so, it would be advisable to dedicate such research to that sole purpose, as this thesis has simultaneously involved learning the 3DEXPERIENCE software and applying the evaluation method onto it with regards of the demands of large enterprises such as Toyota Material Handling.

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Revised evaluation method

Table A.1: General features

Criteria	Classification
Type of package	Data driven simulator Data driven simulator with additional programming capability
Type of simulation	Simulation language Discrete event Continuous Both
Purpose	General purpose Manufacturing oriented Other special purpose
Terminology	General terminology Application specific terminology
Modelling approach	Process based Activity based Event based Three phase Combination
Representativeness of models	High Medium Low
Modelling transparency	High Medium Low
Hierarchical model building	Possible Not possible
Conceptual model generator	Provided Not provided
Support for different operating systems	Mac OS Linux Windows Other

Table A.2: General features, continued

Criteria	Classification
Experience required for software use	None Some Substantial
User friendliness	Formal education in simulation High Medium Low
Initialisation	Possible Not possible
Integration of operations	Provided Not provided
Real-time simulation models	Possible Not possible
Distributed simulation on network environment	Possible Not possible

Table A.3: Visual aspects

Criteria	Classification
Animation	Possible Not possible
Type of animation	Full animation Semi-animation (state-to-state)
Timing of animation	Concurrent animation Post-processed animation
Type of graphical display	Icons Symbols Characters
3D graphics	Provided Not provided
Integrity of graphics	Integrated to the package Separate
Animation layout development	Concurrent with model development Before model development After model development
Multiple screen layout	Flexible Possible Not possible
Facility for customising the view of the model	Provided Not provided
Playback mode	Provided Not provided
Importing graphics and multimedia elements	CAD packages Media Control Interface Bitmap
Animation with visual clock	Provided Not provided
Icon editor	Provided Not provided
Screen editor	Provided Not provided
Icon library	Provided Not provided
Changing the colour of the icons	Possible Not possible Multiple colours
Zoom function	Provided Not provided

Table A.4: Visual aspects, continued

Criteria	Classification
Panning	Provided Not provided
Switching on/off the graphics	Possible Not possible
Switching between character and icon graphics	Possible Not possible
Indication of the element status	Provided Not provided User defined
Virtual reality features	Provided Not provided
Easy copying of icons	Possible Not possible

Table A.5: Coding aspects

Criteria	Classification
Programming flexibility	Provided No additional programming provided
Program generator	Provided Not provided
Access to source code	Possible Not possible
Self-documentation of added code	High Medium Low
Link to a lower language	Possible Not possible
Data storage, retrieval and manipulation facilities	Provided Not provided
Built-in functions	Provided Not provided
User functions	Possible Not possible
Global variables	Provided Not provided
Names of functions, variables, and attributes	User defined System defined
Writing comments for logical elements	Possible Not possible
Type of translation	Compilation Interpretation
Text/code manipulation	Possible Not possible
Support of programming concepts	Provided Not provided
Interface to user written programs	Possible Not possible
Object oriented programming concepts	Provided Not provided

Table A.6: Efficiency

Criteria	Classification
Robustness	High Medium Low
Level of detail	High Medium Low
Number of elements in the model	Large Medium Small
Model reusability	Possible Not possible
Model status saving	Possible Not possible
Automatic saving	Possible Not possible
Interaction with geometrical elements	Possible Not possible
Adaptability to model changes	High Medium Low
Multitasking	Possible Not possible
Model chaining	Possible Not possible
Compilation time	Long Medium Short
Model execution time	Long Medium Short
Various queuing policies	Provided Not provided
Number of queuing policies	Large Medium Low
Time scale for model building	Large Medium Small

Table A.7: Efficiency, continued

Criteria	Classification
Reliability	High Medium Small
Pre-existing generic models	Provided Not provided
Merging of models	Provided Not provided
Editing partially developed models	Possible Not possible
Automatic model building	Provided Not provided
Interactive handling of parameters during experimentation	Possible
Specification of part flow by a mouse	Not possible Provided Not provided

Table A.8: Modelling assistance

Criteria	Classification
Prompting	Provided Not provided
Modularity	Possible Not possible
Model and data separation	Possible Not possible
Facility for designing reusable user defined elements	Provided Not provided
Libraries and templates of simulation objects	Provided Not provided
Warning messages for operations which affect the model file	Provided Not provided
Warning messages for operations which affect model currently developed	Provided Not provided
Context sensitive prompt to facilitate model development	Provided Not provided
Automatic connection between elements	Provided Not provided
Help on system messages	Provided Not provided
Documentation notes for inserting comments concurrently with model development	Provided Not provided
Automatic editing of data	Provided Not provided
Support for point-cloud data	Provided Not provided

Table A.9: Testability

Criteria	Classification
Logic checks	Provided Not provided
Interactive error messages	Provided Not provided
Moment of error diagnosis	Model entry Compilation Model execution
Display of function values	Possible Not possible
Display of attributes	Possible Not possible
Access to attributes	Possible Not possible
Display of variables	Possible Not possible
Display of element's state	Possible Not possible
Dynamic display of capacity	Possible Not possible
Display of the workflow path	Provided Not provided
Display of events on the screen	Provided Not provided
Display of part position within element	Provided Not provided
Facility for immediate user actions	Provided Not provided
List files	Provided Not provided
Echo	Provided Not provided
Trace files	Provided Not provided
Explode function	Provided Not provided
List of used elements	Provided Not provided
Backward clock	Provided Not provided

Table A.10: Testability, continued

Criteria	Classification
Step function	Provided Not provided
Flow analysis	Provided Not provided
Interactive debugger	Provided Not provided
Display of parts flow tracking record collected during simulation run	Provided Not provided
Rejection of illegal inputs	Provided Not provided

Table A.11: Software compatibility

Criteria	Classification
Integration with spreadsheet packages	Possible Not possible
Integration with statistical packages	Possible Not possible
Integration with word processors	Possible Not possible
Integration with computer-aided design software	Possible Not possible
Integration with database management system	Possible Not possible
Integration with expert systems	Possible Not possible
Integration with manufacturing requirements planning software	Possible Not possible
Integration with scheduling software	Not possible Possible Not possible

Table A.12: Input/Output

Criteria	Classification
Menu driven interface	Provided Not provided
Pull down menus	Provided Not provided
Selection buttons	Provided Not provided
Dialogue boxes	Provided Not provided
Multiple inputs	Possible Not possible
Model input	Interactive Batch mode
Database maintenance for input/output	Provided Not provided
Multiple outputs	Possible Not possible
General output reports	Provided Not provided
Static graphical output	Provided Not provided
Dynamic graphical output	Provided Not provided
Types of graphical display	Bar graphs Histogram Level graphs Pie charts Line graphs Scatter diagrams Time series Area graphs
User defined output	Possible Not possible
Automatic rescaling of histograms and time series	Provided Not provided
Periodic output of simulation results	Provided Not provided

Table A.13: Input/Output, continued

Criteria	Classification
Availability of results before end of simulation	Provided Not provided
Input data reading from files	Provided Not provided
Writing reports to files	Provided Not provided
Optimize report for printing	Provided Not provided
Summary reports for multiple runs	Provided Not provided

Table A.14: Experimentation facilities

Criteria	Classification
Automatic batch run	Possible Not possible
Warm-up period	Provided Not provided
Independent replications of experiments	Provided Not provided
Re-initialisation	Provided Not provided
Re-start from non-empty state	Possible Not possible
Breakpoints	Provided Not provided
Speed adjustment	Provided Not provided
Experimental design capability	Provided Not provided
Accuracy check	Provided Not provided
Automatic determination of run length	Provided Not provided

Table A.15: Statistical facilities

Criteria	Classification
Theoretical statistical distributions	Provided Not provided
Number of theoretical statistical distributions	Large Medium Small
User-defined distributions	Possible Not possible
Random number streams	Provided Not provided
User-specified seeds of random number streams	Provided Not provided
Distribution fitting	Provided Not provided
Goodness-of-fit tests	Provided Not provided
Output data analysis	Provided Not provided
Confidence intervals	Provided Not provided

Table A.16: User support

Criteria	Classification
Documentation	Provided Not provided
Reference card	Provided Not provided
Glossary	Provided Not provided
Technical and promotional information material	Provided Not provided
Discussion groups on the internet	Provided Not provided
Lecturer's guide for educational licences	Provided Not provided
Tutorial	Provided Not provided
Training course (basic, advanced)	Provided Not provided
Demo models	Custom tailored training course Provided
Help-line	Not provided Provided
Newsletter	Not provided Provided
Package maintenance	Not provided Provided
Consultancy	Not provided Provided
	Not provided

Table A.17: Financial and technical features

Criteria	Classification
Portability	Provided Not provided
File conversion	Possible Not possible
Price	High Medium Low
Hardware requirements	High Medium Low
Security device	Needed Not needed
Free software trials	Provided Not provided
Free technical support	Provided Not provided
Types of contracts available	Many Not many
Demo models	Provided Not provided
Life cycle maintenance costs	High Medium Low
Price of training course	High Medium Low
Consultancy fees	High Medium Low
Frequency of update	Frequent Not frequent
Comprehensiveness of update	High Medium Low
Discount opportunities	Educational Quantity Other Multiple
Online dependency requirement	None Yes No Semi-dependent

Table A.18: Pedigree

Criteria	Classification
Age	New
	Medium
	Old
Genealogy	High
	Medium
	Low
Spread	High
	Medium
	Low
Success	High
	Medium
	Low
Availability of references	High
	Medium
	Low
Software maturity	High
	Medium
	Low
Reputation of supplier	High
	Medium
	Low
Sources of information about the package	Literature
	Other users
	Supplier
	Demonstration
	Combination of several sources

Table A.19: Environmental consciousness

Criteria	Classification
Degree of LCA coverage	Full Medium Low None
Representative units	CO2e Watts Multiple None
Unit customizability	Possible Not possible
Ability to transform environmental savings into monetary savings	Provided Not provided

Table A.20: Presentation material generation

Criteria	Classification
Level of graphics in development model	Better than presentation graphics Equal to presentation graphics Worse than presentation graphics
Seamless transition between development model and presentation model	Possible Not possible
Quality of data presentation, as compared to dedicated data presentation software	Better Equal Worse
Creation of video	Possible Not possible
User-customizability of video	Customizable Predefined
Creation of 3DPDF	Not possible Possible Not possible

