Cranfield University

School of Aerospace, Transport and Manufacturing
Manufacturing Informatics Centre

Individual Thesis

Digital Re-Distributed Manufacturing (RdM) Studio: Simulation Model Development

MSc in Aerospace Manufacturing | Academic Year: 2015-2016

Author:
Mr Jose Luis Rivas Pizarroso

Supervisors:
Dr Christopher Turner, Dr Ashutosh Tiwari

Abstract

Consumer Goods Industry has gone through significant changes during the last years. A challenging economic climate, advances in technology and shifts in the consumer's attitude have led manufacturers to transform their operating models. Re-Distributed Manufacturing (RdM) aims to address these changes moving towards smaller-scale local manufacture to create a more resilient and connected system, providing not only an agile, user-driven approach that will allow for personalisation and customisation for Product-Service Systems (PSS); but also sustainability through the circular economy.

This research aims to develop a simulation environment based on a current RdM business model, also predicting a future RdM business model based on data-driven decisions. Thus, the model has been employed to compare existing and future RdM scenarios to quantify and spot potential benefits of future RdM models. To achieve this, a System Dynamics Simulation has been built. For this study, changing input parameters regarding recyclability, transportation, the level of automation and level of servitization has been the way of representing the future that RdM will bring to this particular case; showing their impact on operating costs and service efficiency.

The SD business simulation has been validated by experts and is a good example of how data-driven experimentation can predict the future of RdM, with the parameters and variables selected being critical for the model. The simulation model produced by this research showed promising results: operating costs reduced by 40%, PSS revenues in 6 months and immediate response of the system to customer demand.

Acknowledgements

On the completion of this Thesis, I would like to express my deepest gratitude to all those whose kindness and advice have made this project possible:

- I am greatly indebted to my supervisors: Dr Chris Turner and Dr Ash Tiwari, for giving me the chance to contribute to their research, as well as for their guidance and kindness during these months.
- To Dr Mariale Moreno and the people from ShoeLab, for providing the case study for my research and for all the pleasant and productive meetings.
- To the experts from the University of Cambridge, for providing valuable feedback and recommendations for developing my model.

Table of Contents

Abstract 2

Acknowledgements 2

1. Introduction 6

1.1. Document description 6

1.2. Problem definition 6

1.3. Aim and Objectives 6

1.4. Work Planning 6

2. Literature Review 8

2.1. Background 8

2.1.1. Business Background 8

2.1.2. Re-Distributed Manufacturing 10

2.1.3. Servitisation 12

2.1.4. Circular Economy 14

2.1.5. Industry 4.0 15

2.1.6. Systems Dynamics 16

2.2. Business modelling and simulation in RdM 17

2.2.1. High Level Architecture and IMS MISSION project 18

2.2.2. NetMes 19

3. Methodology 21

3.1. Qualitative Analysis 21

3.2. Quantitative Analysis 21

3.3. Model implementation 21

3.4. Model Evaluation 22

3.5. Scenario Generation 22

3.6. Model Validation 22

4. Simulation Model 23

4.1. Case Study 23

4.1.1. ShoeLab overview 23

4.1.2. Intelligent Shoe 24

4.1.3. Customer segregation 24

4.2. Simulation Goals 24

4.3. Assumptions 25

4.4. Model Subsystems 25

4.4.1. Marketing Subsystem 26

4.4.2. Production Subsystem ... 26
4.4.3. Customer Service ... 27
4.4.4. Material Supply Subsystem ... 27
4.4.5. Accounting Subsystem (Cost Analysis) ... 28
4.4.6. Customer Subsystem (AB Model) ... 29
4.5. Scenario generation ... 29
4.6. Model Validation with experts ... 29
4.6.1. Introduction to the validation process ... 29
4.6.2. User community ... 30
4.6.3. On-site interview ... 30
4.6.4. Feedback from experts ... 30
5. Results ... 31
5.1. Dynamic Response of the system ... 31
5.1.1. "As-Is" Scenario ... 31
5.1.2. "To-Be" Scenario ... 31
5.2. Cost-Revenue Analysis ... 32
5.2.1. "As-Is" Scenario ... 32
5.2.2. "To-Be" Scenario ... 33
6. Discussions and Conclusions ... 34
6.1. Contributions ... 34
6.2. Limitations ... 34
6.3. Future research ... 34
6.4. Concluding remarks ... 35
Bibliography ... 36
Appendix ... 38
List of model input parameters ... 38

Table of Figures

Figure 1 Work Planning Gantt Diagram 7

Figure 2 Consumer Goods Value Chain Framework (Oracle, 2016b) 10

Figure 3 Types of RdM with Circular Economy characteristics (Moreno and Charnley, 2015) .. 12

Figure 4 Types of PSS (Tonus, 2014) 13

Figure 5 Circular Economy Framework (Ellen McArthur Foundation, 2016) 15

Figure 6 Inputs, outputs, and interaction between different levels of manufacturing modelling and simulation (Nylund and Andersson, 2010) 17

Figure 7 MISSION Architecture Implementation 19

Figure 8 NetMES key functionality blocks (Helo et al., 2014) 20

Figure 9 Methodology Framework 21

Figure 10 ShoeLab Business Model Framework 23

Figure 11 Customer segregation 24

Figure 12 SD Model 25

Figure 13 Marketing SD Subsystem 26

Figure 14 Production Subsystem 26

Figure 15 Customer Service Subsystem SD Model 27

Figure 16 Material Supply Subsystem SD Model 27

Figure 17 Accounting SD Subsystem 28

Figure 18 AB Model Statecharts 29

Figure 19 Dynamic response to customer demand (“As-Is”) graph 31

Figure 20 Dynamic response to customer demand (“To-Be”) graph 32

Figure 21 Cost-Revenue histogram ("As-Is") 32

Figure 22 Cost-Revenue histogram ("To-Be") 33

1. Introduction

1.1. Document description

The content of this report is divided into seven sections:

1. **Introduction**: aims to introduce the content of the report, as well as the aims and objectives.
2. **Literature review:** contains an extensive research related to the main concepts/topics related to the thesis.
3. **Methodology:** describes the planning and steps followed for the business model simulation.
4. **Simulation model:** describes deep in detail the different features of the model.
5. **Results**: displays and discusses the outputs obtained from the simulation.
6. **Conclusions and discussions**: contains the concluding remarks of the thesis.

1.2. Problem definition

Through the Literature Review, the potential benefits that RdM could bring to CG industry have been spotted. However, it is important to develop tools that enable data-driven experimentation for RdM so that different scenarios can be put into practice. Hence, future RdM business models could be predicted, assessed and optimised. System Dynamics (SD) simulation techniques have not been applied to the area of RdM before. For this research, the primary task is to develop an SD simulation that can collect the primary constraints for a given RdM case study (ShoeLab) and show reliable outputs. Experimenting with different variables to set up an "as-is" and a "to-be" scenario, and compare their results to identify the benefits for future RdM business models.

1.3. Aim and Objectives

The purpose of this thesis is to develop a simulation model that will enable data-driven experimentation with a range of possible scenarios for Consumer Goods industry. SD simulation software will be used to allow for the dynamic visualisation of RDM business models. The main objectives are:

1. Identify an "as-is" RdM business model to employ it as a case study for the simulation (ShoeLab)
2. Set up a reliable SD simulation model to enable its dynamic visualisation, identifying its main constraints and relevant elements.
3. Predict a "to-be" RdM model assisted by data-driven decisions applied to the "as-is" scenario.
4. Compare both scenarios to spot potential benefits for the future RdM.
5. Validate the simulation model with experts.

1.4. Work Planning

This section shows the Gantt Diagram containing the different stages of the process, as well as their duration and schedule:

1. **Research:** Collect papers and information from various sources of information.
2. **Project Brief Elaboration:** Write a report for the sponsors to show the focus and scope of the study.

3. **Literature review**: Summarise the information collected during the research to write the theoretical contribution of the thesis.
4. **Learn Anylogic, SD Modelling and AB Modelling:** Familiarise with the software and the different business simulation techniques employed in the model.
5. **Simulation Model Development:** Build the model that will provide the final results of the thesis.
6. **Thesis Elaboration:** Write the final report shown in this document.

ID	Task Name	Start	Finish	Duration
1	Research	12/05/2016	31/05/2016	14d
2	Project Brief Elaboration	12/05/2016	20/05/2016	7d
3	Literature Review	23/05/2016	20/06/2016	21d
4	Learn Anylogic, SD Modellig and AB Modelling	20/06/2016	07/07/2016	14d
5	Simulation Model Development	07/07/2016	17/08/2016	30d
6	Thesis Elaboration	01/08/2016	29/08/2016	21d

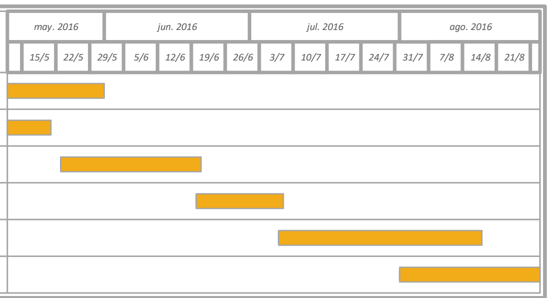

Figure 1 Work Planning Gantt Diagram

2. Literature Review

2.1. Background

2.1.1. Business Background

The aim of this section is to present the current state of the business in consumer goods sector, focusing on Unilever and manufacturing concerns.

2.1.1.1. Consumer Goods Industry

2.1.1.1.1. Market Trends

The industry went through significant changes during the last few years. A challenging economic situation, the advances in technology and the changes in consumer's attitude have led manufacturers to transform their operating models. Some of the challenges faced are (Wood and Wang, 2013):

- User's behaviour has changed: Executives consider client's approach to buying to be shaping the industry for the next ten years.
  - Customers are demanding custom sales order, invoicing and payment processes.
  - Cost effective delivery of particular customer product, case, pallet and display configurations.
  - Increased awareness of the safety of the products.
- Middle-class growth. Middle-class consumption power has grown considerably, especially in developing countries such as India and China.
  - Consumer Goods innovation to diversify into new markets.
  - Infrastructure improvements have allowed for new distribution channels.
- Advances in technology. Technology has had a positive impact on the efficiency of the supply chain.
  - Growing number of data attributes. (Ensuring data quality).
  - Exploring emerging technologies.
- Shortage of natural resources. It is a threat to CG Industry due to the increase of material, energy and transport costs.
  - Invert supply chain to enable recycling activities
  - Standardising sustainability metrics and measurements.

2.1.1.1.2. Business Strategies

Some of the business strategies that Consumer Goods industry is pursuing are (Oracle, 2016a):

- Increase profit margins whereas handling more convoluted supply chains.
  - Supply chain profitability maximisation.
  - Reduce delivery time while maintaining quality.
  - Integrate transport management to control shipping and delivery costs.
  - Manage all aspects of production, delivery and sourcing efficiently.
- Improve inventory management and performance of the suppliers.

  - Achieve more control of delivery timeframes.
  - Attain dynamic visualisation of inventory levels and locations everywhere.
- Monitor supplier performance and prioritise those who perform better. Track every step in the supply chain.
  - Simplify compliance is enhancing product's visibility.
  - Reduce recall costs by tracking products from the supplier to the retailer.
  - Reduce pollution risks by means of visualisation of the key milestones of product's lifecycle.
- Simplify management of complex pricing scenarios.
  - Improve revenue to focus on strategy initiatives.
  - Manage complex and volatiles pricing scenarios with sophisticated calculations.
  - Minimise margin errors to maximise profitability.
- Agility and visibility as means of gaining competitive advantage.
  - Control profitability at every level: manufacturing, production and customer.
  - Shift production to cost efficient centres and give priority to profitable costumers.
  - Improve visibility into critical business metrics.

2.1.1.1.3. Value Chain

Because CG companies offer more product variety to grow in the market, supply chain delays penalise availability of goods. In order to get the products to its desired place at the right time, it is required to implement a demand-driven value chain. (Logility, 2016).

Inventory management is complicated due to the short life cycles of many CG. This has been solved through time-phased policies that allow for accurate forecasts of demand. In order to speed up inventory turns; supply planning must be based on constraints and synchronisation of transportation, distribution resources and manufacturing. (Logility, 2016).

Competition, tight retailer requirements and uncertain gas costs are unavoidable challenges that provoke diminishing margins in the industry. To attain higher profitability levels, CG companies must develop effective demand management programs. (Logility, 2016).

In order to reduce time-to-market, CG companies must optimise and synchronise the supply chain. Business pressures require selecting the best suppliers, production partners and distribution capabilities. A technology platform that enables coordination through these partners is vital, leading to real-time visibility and optimised efficiency into the supply chain activities. Scheduling and capacity constraints need to be shared; to achieve this, real-time information sharing is crucial. (Logility, 2016).

As retailers implement strategies to increase profits, many are requiring suppliers to provide Vendor Managed Inventory (VMI), Value Added Services (VAS) and Just-in-Time (JIT) inventory management. Advanced technology is needed to automatically trigger replenishments based on specific customer needs (Logility, 2016).

Figure 2 illustrates the agents that contribute to this network and how they interact each other:

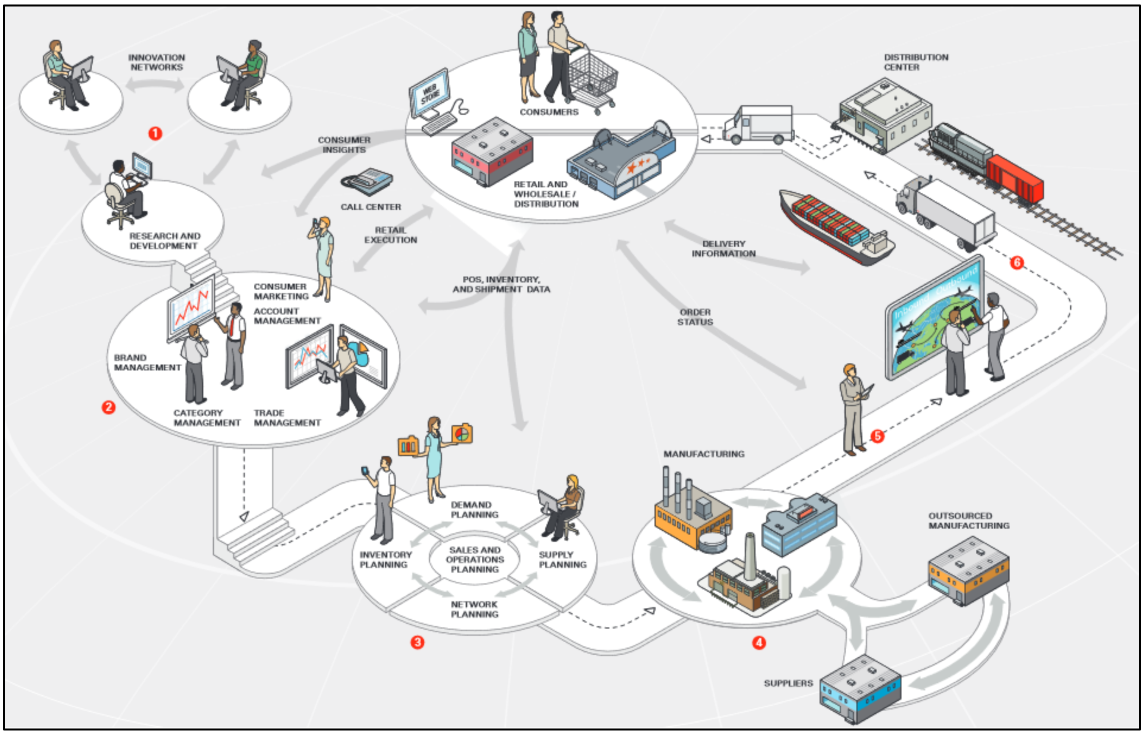

Figure 2 Consumer Goods Value Chain Framework (Oracle, 2016b)

1. Product Lifecycle Management. Reduce cost of innovation, address resilience, reduce complexity, reduce cycle times and enhance the value added by new products (Oracle, 2016b).
2. Sales and Marketing. Optimise the ROI of consumer and trade investments by leveraging consumer and retail insights, integrating sales and marketing processes, and transforming sales operations, thereby improving customer loyalty, trade relationships, promotions, retail execution, brand management, and category management (Oracle, 2016b).
3. Value Chain Planning. Drive profitable revenue growth by integrating the business planning process, synchronising demand and supply, improving demand accuracy, and dynamically responding to demand by optimising company resources across the global network (Oracle, 2016b).
4. Manufacturing. Reduce manufacturing costs, increase yield, improve quality, and effectively respond to demand fluctuations by implementing lean manufacturing, leveraging supply, and outsourcing partners (Oracle, 2016b).
5. Customer Order Management. Enhance customer satisfaction, improve service levels, and reduce out-of-stocks by creating, validating, managing, and fulfilling orders across multiple channels and order-taking processes (Oracle, 2016b).
6. Transportation and Logistics Management. Plan, optimise, monitor, and execute the flow of goods through the supply chain, delivering improved performance and reduced costs (Oracle, 2016b).

2.1.2. Re-Distributed Manufacturing

Future of Manufacturing will be driven by technology, digitalisation, environmental and social aspects that raise new challenges and opportunities for research and business.

‘Re-Distributed Manufacturing’ encapsulates the changes present in value chains, organisational structures and distribution networks are driven by technology, material and engineering advancements, flexible machining and digitalisation. These developments entail shifting towards smaller-scale local manufacturing, caused by changes in transport and labour costs, material, energy and information availability, and the need for sustainability. (Ford and Minshall, 2015).

The Engineering and Physical Sciences Research Council (EPSRC) and the Economic and Social Research Council (ESRC) define RdM as: “Technology, systems and strategies that change the economics and organisation of manufacturing, especially with respect to location and scale. Shifting from centralised to decentralised manufacture with the aim to create a more resilient and connected system taking advantage of digital intelligence and newly emerging technologies, to provide agile, user-driven approach that will allow for personalisation and customisation of products to local markets” (Moreno and Charnley, 2015).

2.1.2.1. RdM Criteria

The RdM criteria classification is (Moreno and Charnley, 2015):

- **Localisation**: RdM aims to decentralise sourcing and fabrication, leading to local manufacture close to the final customer. Therefore, this will result in a geographically distributed manufacturing system.
- **Customisation**: distributed manufacturing could bring a broad range of new practices where clients can alter production from product personalisation to personal fabrication. Customisation is classified into:
    - **Mass customisation**. Mass production for wide markets that meets different needs.
    - **Bespoke manufacturing and information**. Tailors products and services depending on the needs of the users.
    - **Mass/personal fabrication**. Enables open source designs for total customisation for the client.
- **Distributed Ownership**: Digital practices in RdM models facilitate a shift in ownership towards providing products along with services.
- **Distributed Knowledge**: Distributed manufacturing requires total coordination of production networks. Therefore, distribution and information sharing are crucial for RdM.
- **Distributed Structure**: Manufacturing processes decentralisation requires efficient utilisation of global capabilities and flexible logistic systems to attain an integrated supply chain using digital intelligence. This could lead to manufacturers becoming the retailers.

2.1.2.2. Types of RdM

Three types of RdM have been identified explained below (Moreno and Charnley, 2015):

- **Distributed Production and Services**: In this model, RdM employs big data to track production and consumption processes, as well as enabling mass customisation. The value-adding potential of this type is small, as it is very close to the current model, still having core manufacturing activities off-shore.

- **Connected Production and Services**: This type represents an integrated and geographically distributed model. Potential optimisation and value added are high in this model. Although manufacture combines onshore and offshore activities, it is a significant improvement regarding proximity to the user. Big data facilitates client's engagement in a data-driven process with high customisation. Manufacturing and logistics operations are also greatly benefitted from data integration, as well as optimising control of resources.
- **Localised Production and Services:** This is a localised and entirely connected RdM model where all the activities are on-shore, and the manufacturing/retail system is ultimately distributed capturing the highest value from RdM. Clients are greatly engaged in an open design and production process, having consumer goods produced and sold in the same location. This model allows high control of resources and optimisation of operations. This model represents the highest transformation from the current one. Figure 3 Illustrates these types of RdM:

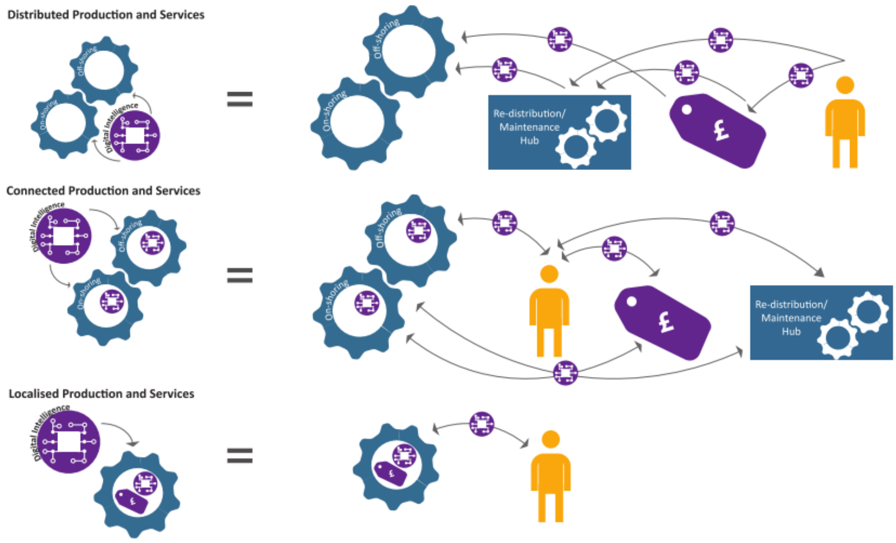

Figure 3 Types of RdM with Circular Economy characteristics (Moreno and Charnley, 2015)

2.1.3. Servitisation

Generally, most people consider products separated from services. Nevertheless, these days have witnessed the servitisation of products and the productisation of services. According to Baines et al., "servitisation is the evolution of product identity based on material content to a position where the material component is inseparable from the service system" (Baines et al., 2007).

Product-Service System (PSS) is a particular type of servitisation. Increasingly, companies develop and market PSS to gain a competitive advantage. PSS involve offerings that include one or more product functionality and one or more associated service functionality. While a company can decide to offer PSS from the start, the usual path towards such an offering is that a company that already provides either products or services adds the missing component to its offerings (Kuijken, Gemser and Wijnberg, 2016). Here the emphasis is on the 'sale of use' rather than the 'sale of product'. The client pays for utilising an asset, not for its purchase, avoiding risks, costs and responsibilities associated with ownership. In a similar way, manufacturers the can enhance their competitive advantage as they differentiate from product-based offerings while keeping asset ownership. This could improve utilisation, design and reliability (Shimomura, Nemoto and Kimita, 2014) (Lee, Yoo and Kim, 2016) (Baines et al., 2007).

2.1.3.1. Types of Product-Service Systems

There have been identified three different types of PSS, listed below (Baines et al., 2007).

- **Product-oriented PSS.** Add a service to a product (Tonus, 2014). It is about selling goods in a traditional way, but including additional services like after-sales service that ensures product durability and functionality (e.g. maintenance or recycling).
- **Use-oriented PSS.** The company maintains ownership (Tonus, 2014). Here the manufacturer sells the use of a product, not being owned by the user (e.g. leasing). Now the company's motivation is to develop a PSS that maximises the use of product required to satisfy the demand, as well as to prolong its life cycle.
- **Result-oriented PSS.** The product is part of the service (Tonus, 2014). The company sells a result and not a product (e.g. Web information replacing directories, selling laundered clothes instead of a washing machine). They offer a personalised combination of services where the mmmanufacturer keeps the product ownership and the user pays for agreed results.

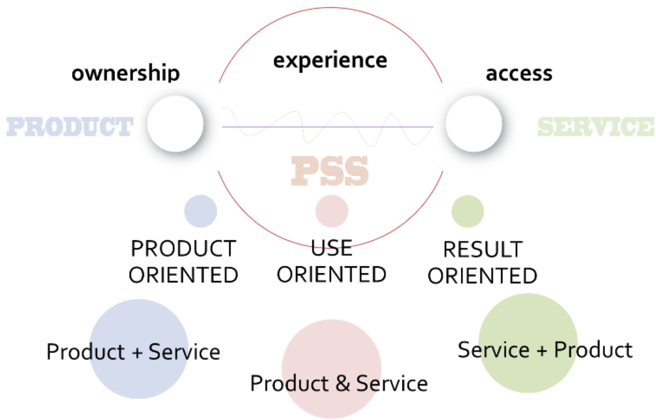

Figure 4 Types of PSS (Tonus, 2014)

2.1.3.2. Benefits of Servitisation

This section describes the main advantages obtained from servitisation (Baines et al., 2007).

- For the customer, a PSS will add value throughout customisation and higher quality (e.g. improved machine availability).
- For traditional producers, PSS is said to bring strategic opportunities for marketing and an alternative to mass production and standardisation. The primary advantage is to enhance in value for the client using increasing services.
- Environmental benefits from PSS include producer responsibility for its products-services, taking them back, reutilising and recycling them.
- For manufacturers, they potentially could use their knowledge to find alternatives to deliver the same value while using less energy and materials, reducing costs and helping the environment.

- For a State and the global environment, PSS can result in a reduction of resources as fewer goods are produced, reducing the material per use. As well as that, providing these services could help to compensate the loss of jobs in traditional manufacturing.

2.1.4. Circular Economy

Because of growth in industrial activity, pollution, waste and landfill are becoming more and more threatening. Besides, the middle-class growth led to a higher demand for resources, which is a risk for the scarcity of natural resources. (Lieder and Rashid, 2016).

This situation requires manufacturers to deal with tight environmental legislations, challenges related to price volatility and supply chain resilience. Competition for scarce or critical raw materials has become a major concern as well (Lieder and Rashid, 2016). It is hence known that resource efficiency and security are vital for future resilience and competitiveness. This scenario asks for a fundamental rethink on the functions of resources in the economy (Preston, 2012).

Provided the presented challenges and the constraints of a linear economy, the concept of a circular economy represent an alternative for combining economic growth and environmental protection. A circular economy is "the realisation of closed loop material flow in the whole financial system" (Lieder and Rashid, 2016).

A circular economy is designed thinking in restoration and regeneration, aiming to achieve maximum utilisation and value of products, components and materials. A circular economy is a cycle that preserves and improves natural capital, maximises resilience and optimises resource yields by handling renewable flows and limited stocks. It must be efficient at every scale.

2.1.4.1. Principles of the circular economy

The main principles of circular economy are listed as follows (Ellen MacArthur Foundation, 2015):

1. **Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows.** When there is a need for resources, the system chooses them wisely and selects processes that employ renewable or efficient resources when possible.
2. **Optimise resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles**. This implies recycling and remanufacturing to keep core components and materials in circulation, contributing to the economy. Circular systems use tighter, inner loops (e.g. maintenance, rather than recycling) if possible. A circular economy aims to increase product utilisation by prolonging product's life and supporting reuse.
3. **Foster system effectiveness by revealing and designing out negative externalities.** This includes reducing damage to systems and areas such as food, mobility, shelter, education, health, and entertainment, and managing externalities, such as land use, air, water and noise pollution, and the release of toxic substances.

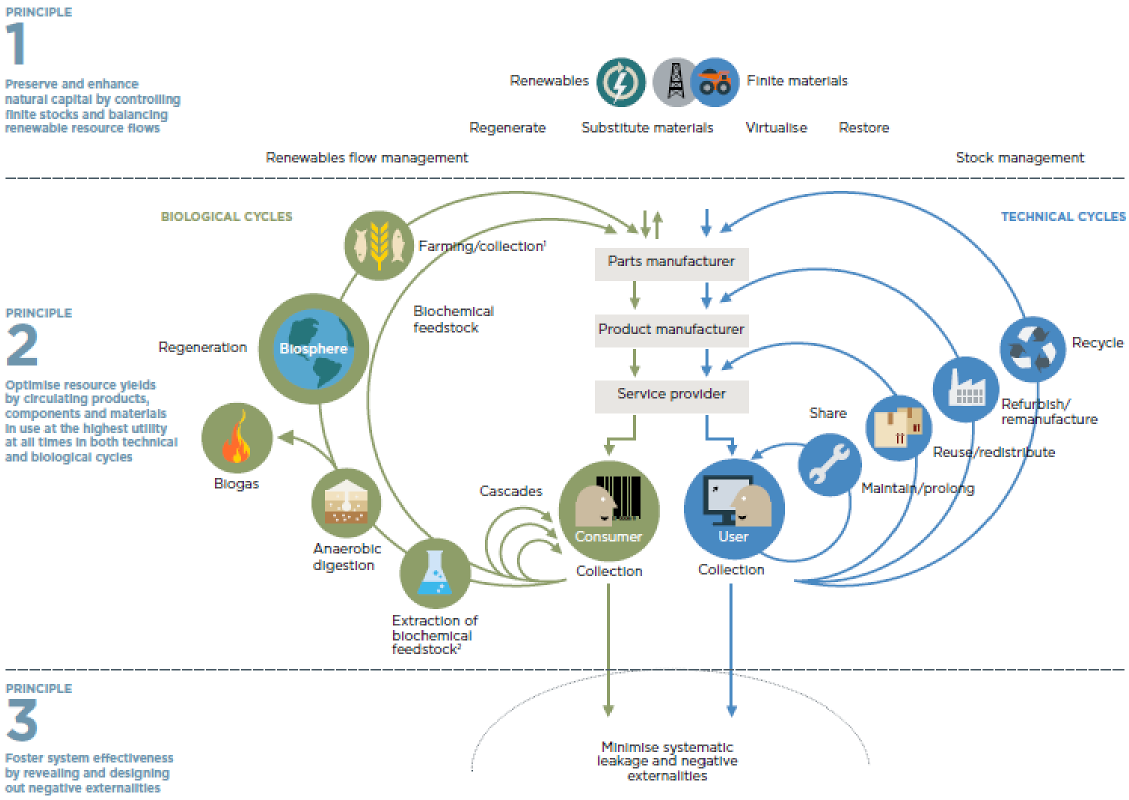

Figure 5 Circular Economy Framework (Ellen McArthur Foundation, n.d.)

2.1.4.2. Economic Opportunities of Circular Economy

The economic opportunities of seeking CE are (Witjes and Lozano, 2016) (Ellen MacArthur Foundation, 2015):

- **Economic growth**. Increasing profits from circular activities combined with lower production costs through effective utilisation are set to achieve economic growth. These changes in manufacturing activities affect supply, process and demand; benefitting all the sector of the economy and leading to a series of effects that contribute to the overall growth.
- **Substantial net material cost savings**.
- **Job creation potential**. High-quality recycling activities required skilled workers in remanufacturing. Moreover, the expected increased spending powered by lower prices can be attributable to the job creation. The new service-based economy will increase innovation and entrepeneurship.
- **Innovation**. The pursue of replacing one-way goods by products that are circular by design and reverse logistics networks is a remarkable spur to new ideas.

2.1.5. Industry 4.0

Industry 4.0 (also known as smart industry) makes reference to the technological advancements evolving from embedded to cyber-physical systems. Represents the coming fourth industrial revolution giving way to Internet of Things, Big Data and Services. Distributed intelligence enables intelligent object networking and managing processes independently. Industry 4.0

implies a shift from centralised to decentralised production, made possible by technology advancements. In other words, the industrial machinery no longer just processes products, but the products interacts with machines and orders them what to do (Dauner and Löbig, 2014) (Sendler, 2013) (CRO Forum, 2015).

Most advances in technology described in this section have been already implemented in manufacturing. However, with Industry 4.0 production will be transformed: isolated and optimised cells will become a fully integrated, automated and optimised production system. This will result in more efficient production network relationships not only between agents but also between human and machines. Rüßmann and Lorenz identified the nine pillars of technological advancement (The Government Office for Science, 2013) (Rüßmann and Lorenz, 2015):

1. **Big Data and Analytics.** Extensive data sets analysis has emerged recently in manufacturing as a way of optimising production quality, saving energy, and enhance equipment service. Collecting and evaluating data from various sources will help to support real-time decision-making.
2. **Autonomous Robots**. Robots are evolving to become more autonomous, cooperative, and flexible. Future robots will communicate each other and work safely with humans. The idea is to reduce operation costs and increase flexibility through a broader range of capabilities.
3. **Simulation.** Forthcoming simulations will be present at every stage of the manufacturing plant. Machines will collect data to mirror the physical process with a simulation model; assisting decision-making, reducing set up times and improving quality
4. **System Integration.** With Industry 4.0, every department of different companies will be fully integrated, enabling data sharing, automated value chains and cohesion of capabilities.
5. **The Industrial Internet of Things.** This technology will allow independent devices to communicate and interact with centralised controllers. This will enable real-time responses, decentralising decision-making and analytics.
6. **Cybersecurity.** Due to the connectivity revolutions that brings smart industry, the necessity to protect crucial industrial systems from attacks or threats is dramatically bigger. Thus, reliable and safe communications are essential.
7. **The cloud.** Industry 4.0 will require the storage and access to significant amounts of data. Eventually, machinery data and functionality will be deployed to the cloud, allowing for more data-driven services for manufacturing systems.
8. **Additive Manufacturing.** With industry 4.0, the use of additive manufacturing methods will be broadly employed to produce small batches of parts and enable customisation. High-performance decentralised 3D-printing systems will reduce transportation and inventory.
9. **Augmented Reality.** Augmented-reality-based systems permit multiple services, for instance choosing parts in a warehouse and sending instructions over portable devices. In the future, companies will make much wider use of augmented reality to provide workers with real-time information to improve decision making and work procedures.

2.1.6. Systems Dynamics

System Dynamics (SD) theory started as a way to forecast the behaviour of dynamic systems and analyse the decision-making. In the literature, SD modelling has been broadly employed to assess the resilience in industrial environments. For example, SD has been aplied to supply chain management to handle inventory management, strategy assessment and bullwhip effect. (Li, Ren and Wang, 2016).

SD modelling reflects the changes in the behaviour of the system components over time. In a developed causal loop diagram, the assumed interactions between the variables are formalised to demonstrate the interdependence within the system boundaries. A closed chain of causal relations is defined as the feedback loop, which could be positive or negative. The positive loop is unstable and oscillated that triggers systems to grow, evolve and collapse, while the change of negative loop towards a stable situation (Li, Ren and Wang, 2016) (Yearworth, 2014).

2.2. Business modelling and simulation in RdM

Al-Debei define business model as "abstract representation of an organization, be it conceptual, textual, and/or graphical, of all core interrelated architectural, co-operational, and financial arrangements designed and developed by an organization presently and in the future, as well as all core products and/or services the organization offers, or will offer, based on these arrangements that are needed to achieve its strategic goals and objectives". This definition tells that value proposition, value finance, value architecture value network and value proposition constitute the main dimensions of business models (Al-debei, 2008). The objective of using business modelling is to reduce the complexity of company design, increase coherence, optimise its structure and analyse its operations (Fayoumi, 2016).

Manufacturing is one of the fields in which simulation is most broadly used. Simulation is very powerful to design manufacturing systems or enhance existing one's performance. Modelling and simulations are performed to understand how the system behaves to achieve a specific result, to find out what happens and why, to refine manufacturing capabilities for its continuous improvement or to adapt it to a different context. (Nylund and Andersson, 2010).

There are three different levels in business environments: the macro area is focused on organisations, the meso area is based on processes and the micro area is about individuals or small groups. The macro level works on system level, evaluating for instance a manufacturing plant as a whole; the meso level deals with processes involving various sub-processes (focuses on operations management); the micro level is intended to investigate individual activities such as a the machining of a piece (Nylund and Andersson, 2010).

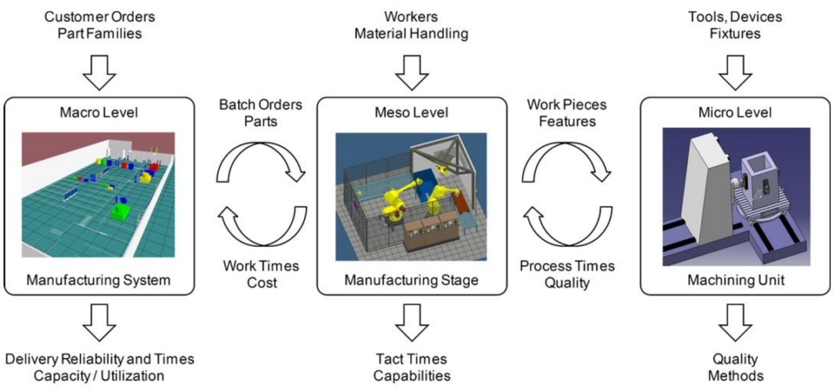

Figure 6 Inputs, outputs, and interaction between different levels of manufacturing modelling and simulation (Nylund and Andersson, 2010)

2.2.1. High Level Architecture and IMS MISSION project

2.2.1.1. High-Level Architecture (HLA)

HLA is software architecture for distributed simulation aiming to support a wide range of different simulation approaches and applications. It constitutes a framework and sets up functional rules and interfaces for integration of independent simulators into a bigger one. The purpose of the HLA is to reduce software costs by facilitating the reuse of simulation components and by bring a runtime infrastructure to control the simulations. Hence, flexibility is one of its the main goals. Particularly, the HLA addresses two critical challenges: support interoperability between simulations and aiding the reuse of models in different contexts (Uygun, Öztemel and Kubat, 2009).

HLA defines an individual simulation as a federate, and a set of unites as a federation. It is formally defined by three components:

- Interface Specification (IS): describes the runtime services provided to and by the federates.
- Object Model Template (OMT): provides a standard presentation format for HLA federates. Using the OMT, each federate defines, in its simulation object model (SOM), the data that it is willing to share with and requires from other federates.
- Rules: express the requirement that all the federations and federates have to satisfy. The rules also define the fundamental principle that the federated have to obey.

One of the most important projects aimed to implement distributed simulation techniques to the industry is IMS MISSION project. The objective of the project is to support simulation applications of globally distributed or virtual enterprises using High-Level Architecture (HLA) (Uygun, Öztemel and Kubat, 2009).

2.2.1.2. IMS MISSION project

The purpose of MISSION is the integration of new technologies of distributed data management, as well as traditional tools and methods, in diverse company environments, to meet the needs of globally distributed enterprise modelling and simulation. This allowed for an architecture to support engineering cooperation across the value chain of the entire company (McLean and Riddick, 2000).

Four principal work packages contribute to MISSION projects (Melorose et al., 2001):

- Requirement definition
- Development of an integration infrastructure
- Development of application components
- Test cases and demonstrators

The HLA enables merging diverse simulations into a single, global one. The HLA met many needs for distributed simulations such as time synchronisation or interactions between independent simulation models (McLean and Riddick, 2000).

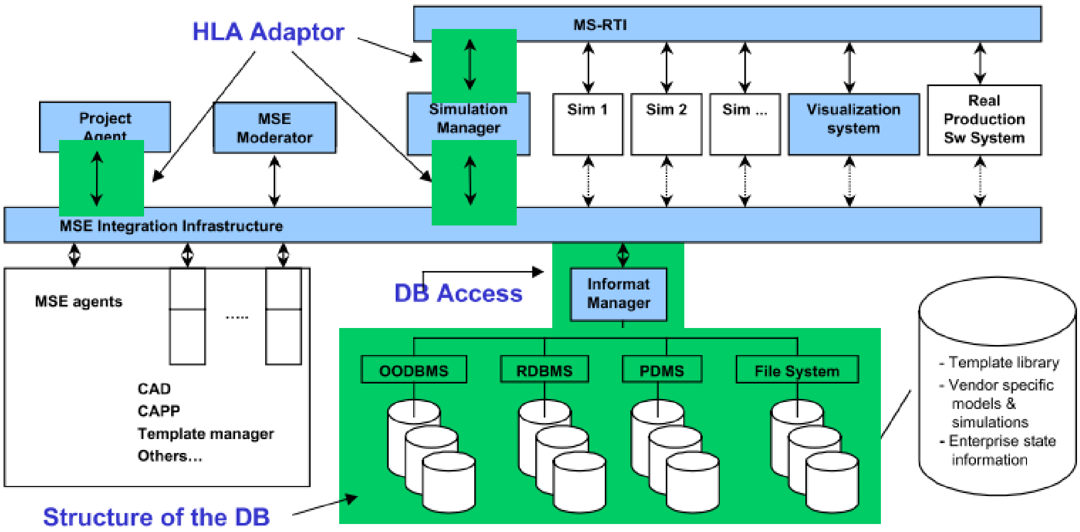

Figure 7 MISSION Architecture Implementation

2.2.2. NetMes

Helo et al. illustrated the needs and challenges for the management of distributed manufacturing in a multi-company supply chain and processed these as features of new IT systems. The requirements and difficulties in data integration inside Small and medium-sized (SME) networks are firmly related to the constraints of prevailing supply chain solutions. Present ERP-solutions do not provide extended company support nor shared cloud-based information. However, current MES solutions are valid for manufacturing processes, but failing for distributed manufacturing. To address these specifications, Helo et al. developed a software tool to support the needs related to real-time, cloud-based, lightweight operation (Helo et al., 2014).

This solution is based on of virtual companies, which combines the power of several independent enterprises to achieve complex manufacturing processes. When an organisation gets a new request from a client, it can be converted to manufacturing orders, and different factories will be chosen and selected for to the production processes. Conversely, this MES can be used to collect real-time information from the system and transform this information into the higher-level organisation (Helo et al., 2014).

Although this solution focused on the primary requirements, it included new sequencing algorithms for business process and planning and a new infrastructure based on existing MES technology. In this solution, the cloud acted as a platform for the evolution of MES. Since cloud computing is already practical at the business level, they built MES based on web services providing a standard for data-sharing environments. Cloud technology was adopted to support tracking, information exchange and also other real-time communications (Helo et al., 2014).

Most manufacturers use ERP to determine the production planning process. NetMES is used to translate this plan into work instruction, and build the method of managing real resources and real plant floor execution. The NetMES system is a web browser based MES system for distributed (multi-site) production planning and control system. The key features of the system include (Helo et al., 2014):

- Support for multi-site manufacturing
- No installation required – a web based system
- Connections to external systems such as ERP
- Tracking and tracing within the entire extended enterprise
- Providing KPI data master for production

This concept depends on external master data stored in the ERP system. The system is focused on capacity management, work queue, and tracking information within the company to connect the factory floor to the executive levels of the enterprise. It collects orders from the ERP system, and converts this requests into an execution order and passes process instruction to the control automation system. After product operation and implementation is done, it updates the status of the product and sends the information back to NetMES (Helo et al., 2014).

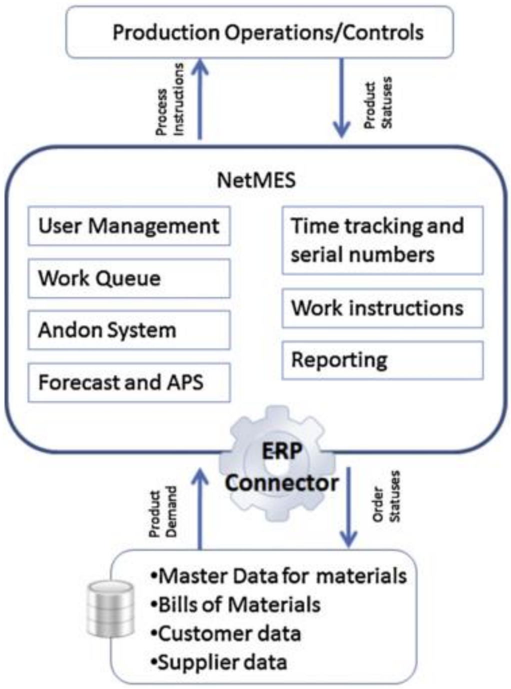

Figure 8 NetMES key functionality blocks (Helo et al., 2014)

3. Methodology

In this section, the different steps followed to develop the SD model will be explained. Figure 9 outlines the framework for the methodology followed:

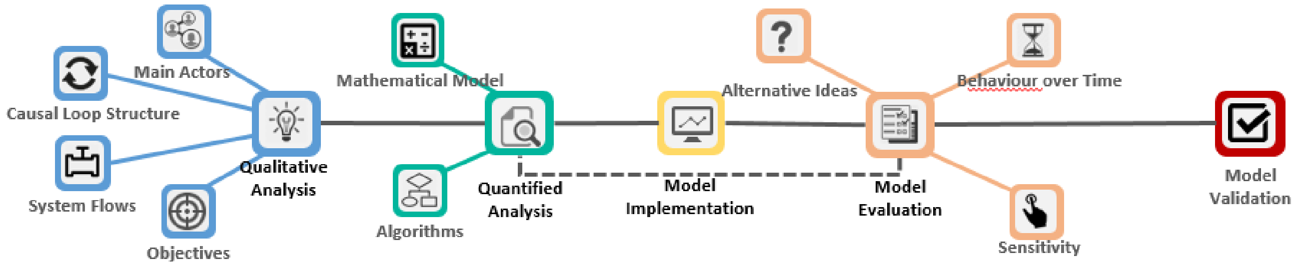

Figure 9 Methodology Framework

3.1. Qualitative Analysis

The goal of the qualitative analysis is to map the value chains and the different network interactions across the system that are relevant for the study. Provides a perspective on the observed problem.

- **Set simulation objectives.** Identifying the outputs that must be obtained from the simulation is crucial to differentiate which elements/variables are relevant for the study and which are negligible. Not selecting the most appropriate outputs could lead to redundant results or unnecessary data requests.
- **Identify main elements.** Once spotted the objectives, the next step is to choose which features/processes/variables contribute or influence the outputs.
- **Draw causal loop and system flow structures.** When all of the actors are on the table, it is necessary to start grouping them in subsystems, as well as define their relationship. For SD modelling it is crucial to determine which of the variables are going to be stocks, how other variables influence the flow between them, and the causal loops that are present in the entire system.

3.2. Quantitative Analysis

The purpose of this part is to quantify the problem and generate numerical data. This will be crucial to enable data-driven experimentation and set different scenarios for the model.

- **Mathematical Modelling**. This step is about finding the mathematical expressions that relate the different variables and parameters. Dimensional analysis is often useful for this part, especially for the expressions related to flows.
- **Input Parameters value.** To obtain reasonable results, it is vital that the figures introduced in the model be coherent and realistic. Often it is necessary to make assumptions and do extensive research to estimate valid values.
- **Logic Structure.** Many interactions between systems can often be modelled as algorithms. It is important to recognise which conditions, orders, timeouts and so on are present so that the system can behave as expected.

3.3. Model implementation

After defining the model, the next step is to implement it in a simulation software. It is important to be familiar with the tool to optimise the quality and reliability of the model.

3.4. Model Evaluation

This part is necessary to perform the continuous improvement of the robustness and reliability of the SD model.

- **Behaviour over time.** After running the model, it is vital to observe how the different variables change over time to check that everything goes as expected and identify errors.
- **Sensitivity Study.** This consists of running the simulation several times changing the value of a parameter to see how it affects to the final result. This helps to identify the key drivers in the system.
- **Alternative Ideas.** This part aims to improve the model by challenging it with alternative features; this contributes to the continuous improvement.
- **Data-driven experimentation.** Experiment by changing different values to spot possible scenario improvements.

3.5. Scenario Generation

The purpose of this part is to obtain a "to-be" scenario starting from the "as-is" one just by changing the data of some parameters.

- **Select change drivers.** It consists of determining the key parameters that are going to drive the change from the current to the future scenario.
- **Define values.** After selecting these inputs, it is necessary to predict how these are going to change in the future.

3.6. Model Validation

The aim of this step is to verify that the built model is reliable and can be the object of study. It consists of interviewing an expert in the field of study, providing a questionnaire to be filled for them.

4. Simulation Model

This section aims to describe the simulation model obtained by following the methodology detailed in section 3.

4.1. Case Study

4.1.1. ShoeLab overview

ShoeLab is an initiative collaboration by Cranfield University, Cisco, and The Clearing to develop smart and sustainable shoes. The term "smart" and "sustainable" are simplifications of the actual effort: to utilise digital intelligence, redistributed manufacturing, and product- service system to develop circular product and business model. Figure 10 Shows the value chart for ShoeLab business model.

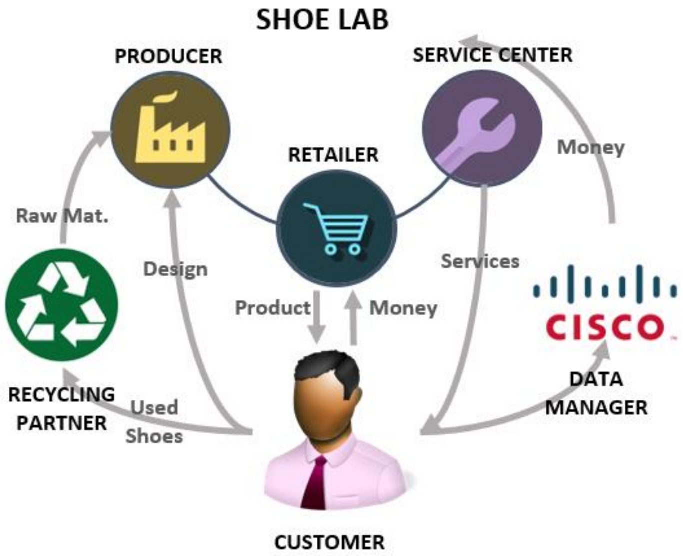

Figure 10 ShoeLab Business Model Framework

The primary agents within ShoeLab are:

- **Producer:** Manufactures the Shoes according to the customer demand. It integrates the supply chain, fabrication and transport. It interacts with the customers by responding to their demand and satisfying the customisation required by them.
- **Retailer**: Is in charge of the retail and delivery of the product. It delivers the product to the client and receives the subscription fee paid by them.
- **Service provider:** Its duty is to ensure services such as repairing or refashioning of the shoe. Again, responding to the customer's demand for these services.

Other stakeholders that take part in the business are:

- **Data Manager:** Cisco Systems sponsors and supervises the ShoeLab project and is supposed to be the data management partner. It is willing to pay a fee for the data gathered from the clients' shoes.
- **Recycling Partner:** Its duty is to process the material coming from wasted shoes to reutilize them.

4.1.2. Intelligent Shoe

The product developed by ShoeLab consists of a 3D-printed intelligent shoe that aims to provide customisation for the client and integration of multiple electronic devices.

The customer will get a shoe that fits perfectly to them using 3D-scanning and 3D-printing. Moreover, the client will be able to customise the design of their shoes.

The idea is that the user will have no need for carrying any other object while running. Thus, this intelligent shoe will combine functions from different electronic devices:

- Multimedia
- Activity tracking and monitoring
- Payments
- Electronic Key System

4.1.3. Customer segregation

Three types of customers have been spotted for this business model:

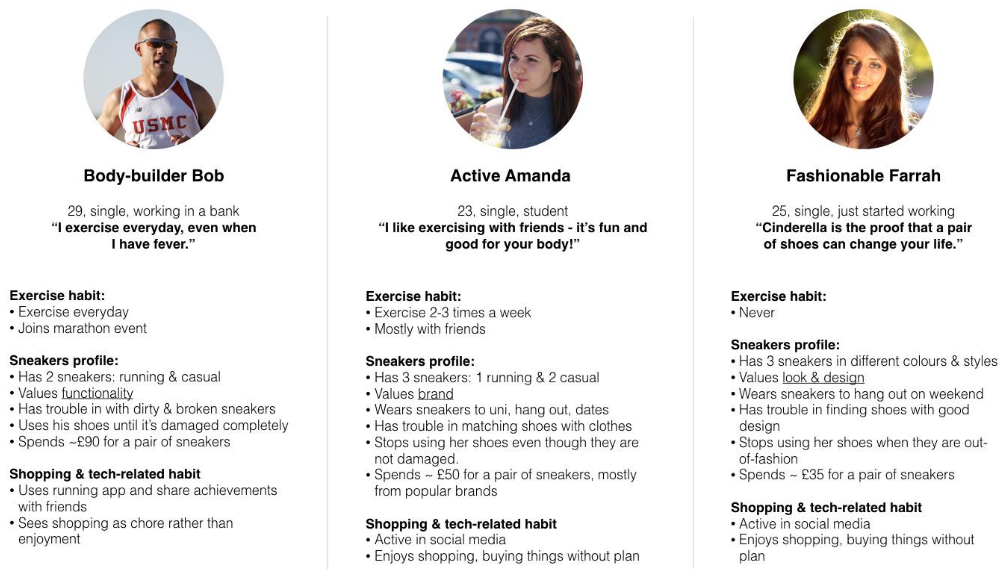

Figure 11 Customer segregation

4.2. Simulation Goals

The SD simulation of the case study has five main objectives:

- Obtain the temporal response (retard) of the system to the client demand
- Create an AB model that considers the customer segmentation and simulates the client's demand for services
- Analyse the cost implications for the PSS and its profitability
- Make recommendations for product prices and capacity requirements for ShoeLab
- Enable data-driven experimentation to allow for multiple scenarios. Particularly, one that predicts the future RdM model.

4.3. Assumptions

The assumptions considered for this model are:

- Both 3D-printing and Shoe technology are deemed to be in the maturity phase of its life cycle, for the current and the future scenarios. Otherwise, the cost would be extremely high, and no comparisons or conclusions could be obtained.
- The costs have been estimated basing on the percentages provided by Solereview (Solereview, 2016)
- All the input parameters and variables take the value showed in the table of the Appendix.

4.4. Model Subsystems

This section is intended to describe the different subsystems present in the simulation model. However, the effectiveness of the model comes from the complex interactions between those subsystems. Figure 12 shows the whole model and the interactions of all the variables. The complexity of explaining the entire model is the reason why this section is going to tell it divided into five subsystems.

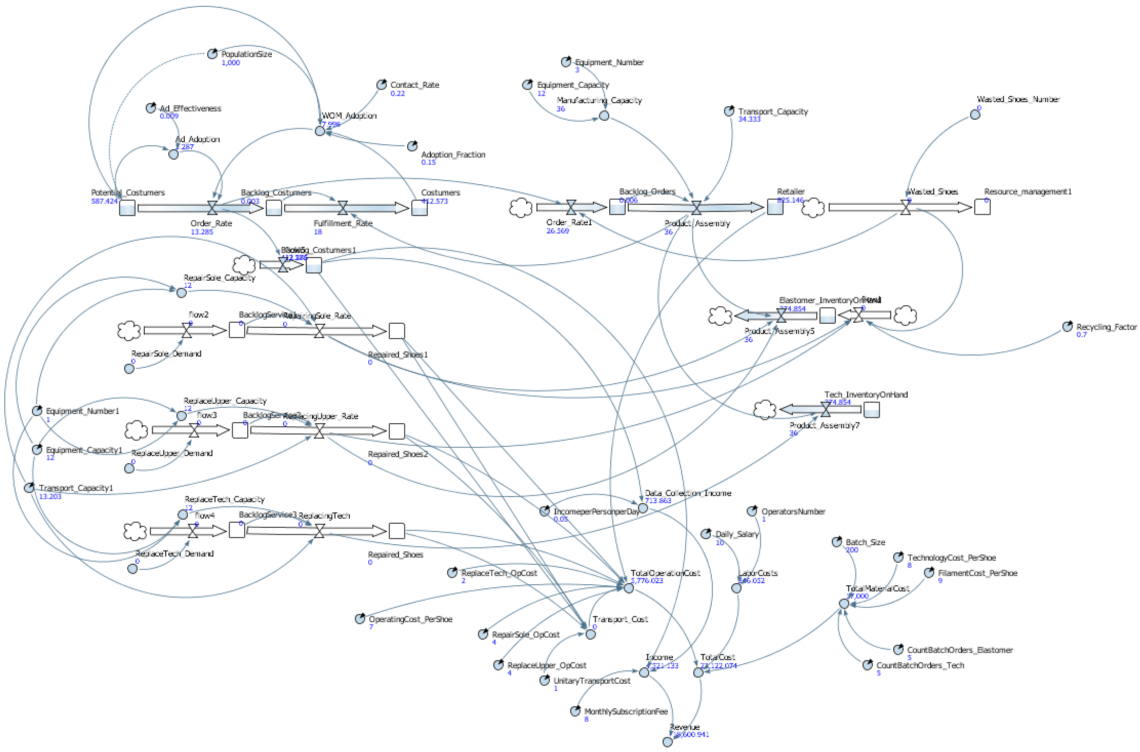

Figure 12 SD Model

4.4.1. Marketing Subsystem

The aim of this SD subsystem is to model the demand for hiring the service. Details how publicity and word of mouth affect the rate of adoption of the product. Figure 13 shows the simplified system flow and causal loops for this subsystem.

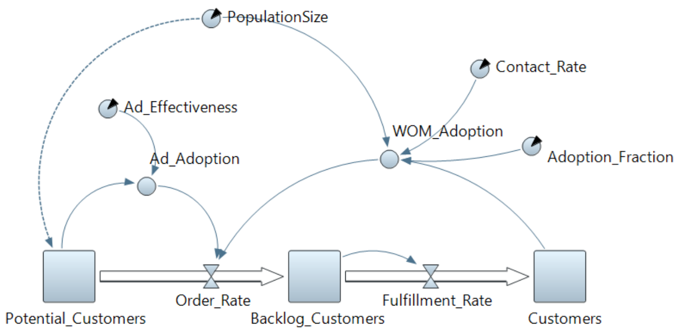

Figure 13 Marketing SD Subsystem

Here the flow of population goes from Potential Costumers, which are equal to the Total Population Size; to Backlog Customers, which are clients that have subscribed without receiving their product yet; to Customers, who have already got their shoes. The “Order/Adoption Rate” depends on the adoption due to “Advertising” plus “Word of Mouth”; the “Fulfilment Rate” depends on the Production, described below.

As well as that, this model can show the system transient response to the demand (retard), driven by the “Fulfilment Rate”.

4.4.2. Production Subsystem

The purpose of this SD model is to measure how manufacturing and transport capabilities affect the lead time and delivery time. The primary output of this model will be the “Fulfilment Rate”, commented above. Figure 14 depicts a simplified version of the SD diagram for this part:

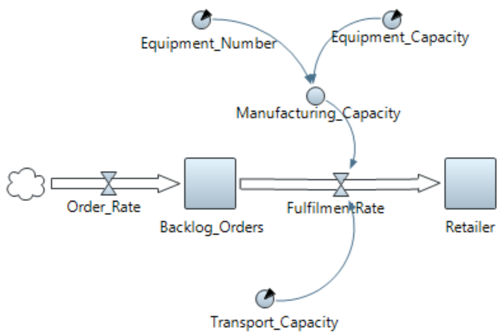

Figure 14 Production Subsystem

In this case, the stocks represent products, going from “Backlog Orders”, which represent the pending orders computed by the Marketing Subsystem; to the products fulfilled to the “Retailer”. Again, the flow between both stocks depends on the transport and fabrication capabilities.

4.4.3. Customer Service

This model acts like the Production Subsystem but focusing on satisfying customer demand for services. This part is imperative as the business model is a Product-Service System, it will help to measure the implications and costing of providing these services. Figure 15 shows the SD model for one and the three services put together.

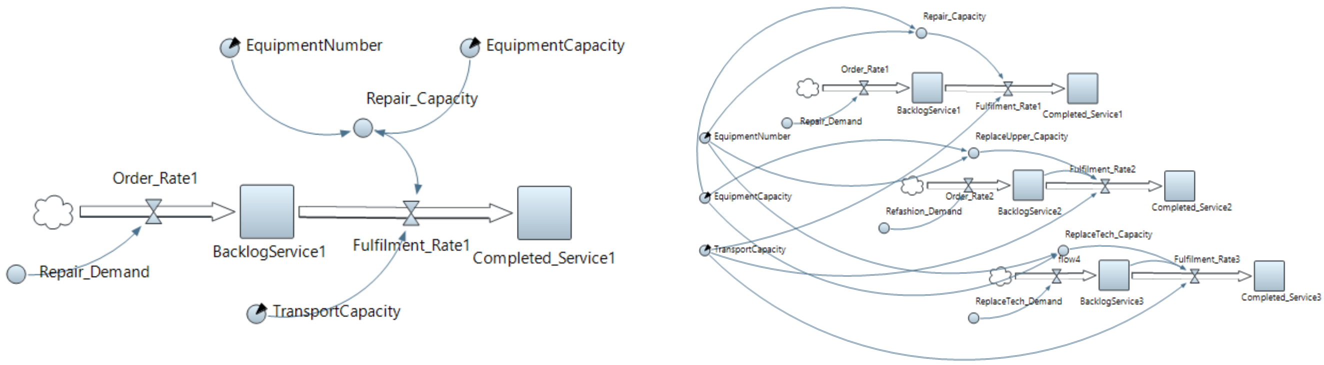

Figure 15 Customer Service Subsystem SD Model

In this subsystem, the stocks contain services, where “Backlog Services” includes the pending services to be completed. The customer demand for services is triggered by an AB Model described in section 4.4.6. ; the “Fulfilment Rate” is computed very similarly to the Production Subsystem.

4.4.4. Material Supply Subsystem

This subsystem aims to model the raw material resources of the system. It handles the inventory management, the material supply and the recycling of wasted products. Figure 16 shows a simplified representation of the SD Model subsystem:

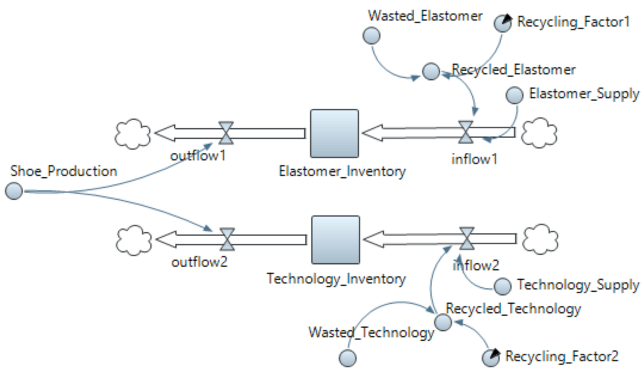

Figure 16 Material Supply Subsystem SD Model

The stocks represent the “On-Hand Inventory” of the raw materials or subassemblies required for the production. The “Inflow” of material will depend not only on the suppliers but also on the recycling from “Wasted” products or parts from other shoes; thus, the recycled material will be computed from the Customer Subsystem (AB Model) and the Customer Service. The “Outflow” of materials will depend on the material request from the Production Subsystem.

4.4.5. Accounting Subsystem (Cost Analysis)

This subsystem aims to compute the desired output for the simulation: the economic balance through the system. It collects data from the primary cost driver and income sources.

The main cost drivers taken into account for this analysis are listed as follows:

- **Operational Costs.** Costs including machinery usage, machinery depreciation, energy consumption, material storage,oral transportation.
    - Shoe Fabrication
    - Repair Service
    - Refashion Service
    - Replace Service
    - Recycling Costs
    - Transport
- **Labour Costs.** Cost associated to the workforce needed for the system.
    - Operator Salary
- **Material Costs.** Cost of the materials necessary for fabricating the product.
    - Elastomer
    - Tech Subassemblies

The main sources of income are:

- **Monthly Subscription Fe**e. Expenses provided by PSS customers every week
- **Data Collection**. Fees paid by the Data Manager Partner for selling the data collected from clients' intelligent shoes

All of this variables are part of the Accounting Subsystem integrated into the SD Model. This subsystem interacts with all of the rest to track the temporal evolution of costs and incomes. Figure 17 shows the SD model, where the multiple links coming from other subsystems can be appreciated.

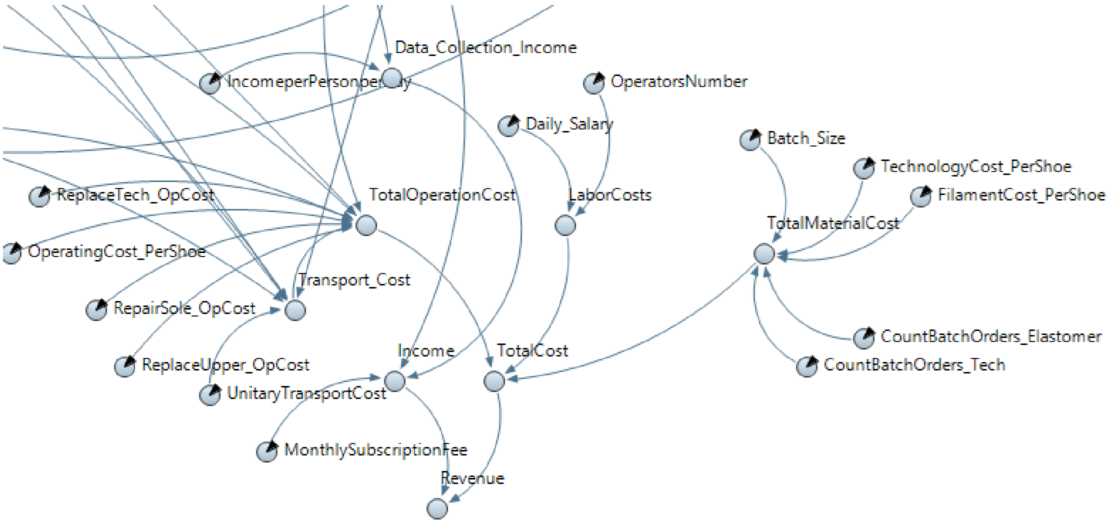

Figure 17 Accounting SD Subsystem

4.4.6. Customer Subsystem (AB Model)

The aim of this AB System is to model a population of costumers who, using statecharts, will be able to simulate the service demand and hence trigger the SD Model. The statecharts determine the state of every customer regarding service need. Timeouts or conditions trigger the transition between states, varying on each client depending on their persona distribution ("Fashionable"," Active" or "Body Builder"). Figure 18 shows the different statecharts applied to the agents (clients).

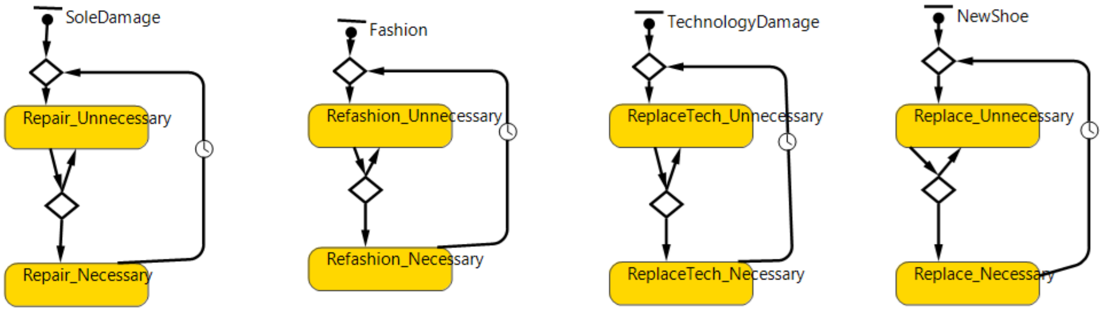

Figure 18 AB Model Statecharts

4.5. Scenario generation

For the completion of the study, it was essential to recreate two different scenarios ("as-is" and "to-be"). The current one was based on the actual ShoeLab business model and incorporating the assumptions made in 4.3. The "to-be" scenario needs to be obtained applying data-driven experimentation to the "as-is" one.

From this starting point, to predict a future RdM business model, it was assumed that three different sources of data would be subject to change in the future:

- **Recyclability**. Recyclability of raw materials will be a must in the future of RdM to ensure circular economy and sustainability.
- **Transportation**. Coming RdM aspires to minimise shipping costs by fabricating on site.
- **Level of automation.** The smart factory is known to be the future of manufacturing, minimising the human workforce.

The values given for each parameter in both cases are detailed in the Appendix.

4.6. Model Validation with experts

4.6.1. Introduction to the validation process

This section describes the model validation process as it is part of the described methodology in section 3.6. It was vital for the study to ensure that the developed tool, as well as the results provided by it are reliable. Thus, one meeting was arranged to expose and allow the simulation model and get direct feedback from experts in business models and simulation. The idea was to make sure that the model captured all the relevant aspects of a RdM environment, that the value chain and network relationships were represented, that the input data, variables and outputs collected the primary constraints of the system, and that the results obtained are sensible and reliable.

4.6.2. User community

The user community selected for validating the model were industry experts with experience in business modelling and simulation applied to RdM and circular economy. The experts are from Institute for Manufacturing (IfM, University of Cambridge), who collaborate with RECODE network in similar projects. As well as that, researchers involved in the Case Study (ShoeLab), who have personally built the business model, were interviewed to ensure that the simulation tool was as close as possible to reality and described the business perfectly.

4.6.3. On-site interview

Before the written questionnaire. The agenda for the meeting started with their presentation, where they showed their areas of research and their vision in business modelling, RdM and circular economy, followed by the presentation and demonstration of the model and ending with a feedback session.

The aim of the presentation was to make sure that the interviewees fully understood the case study, so they could provide more valuable feedback. Clarity when exposing the model was vital, detailing all the different aspects from the different SD subsystems and AB model. This was achieved successfully as the experts were engaged and collaborative through all the interview.

4.6.4. Feedback from experts

After exposing the goals, demonstrating how the model worked and the output obtained, the interviewees agreed on the scope of the study, the representation of the case study elements and constraints, and the sensibility of the results obtained.

It was important to collect feedback regarding data-driven scenario generation and how the RdM situation would change in the future. Finally, there was an agreement on the selection of transportation, level of automation (human workforce) and recyclability. Other alternatives like level of servitisation and customisation were suggested.

To contribute to the continuous improvement of the model, there were also suggestions in terms of input data values and constraints that would affect the system.

Regarding the assessment of the model, the experts agreed that, despite the constraints in terms of accuracy, the model stands out for its completeness and the quality of the results in terms of providing trends and valuable comparison between scenarios. All the subsystems were said to capture all the variables/elements relevant for the study, highlighting the level of detail in their interactions.

5. Results

5.1. Dynamic Response of the system

The dynamic response measures how a system reacts to a given input. In this case, the input studied for the SD model will be the output from the AB Model. In other words, how the manufacturing/service system reacts to the customer demand and how long does it take to fulfil it.

5.1.1. “As-Is” Scenario

Figure 19 shows the product/service accumulated demand against the fulfilled demand for the “as-is” situation.

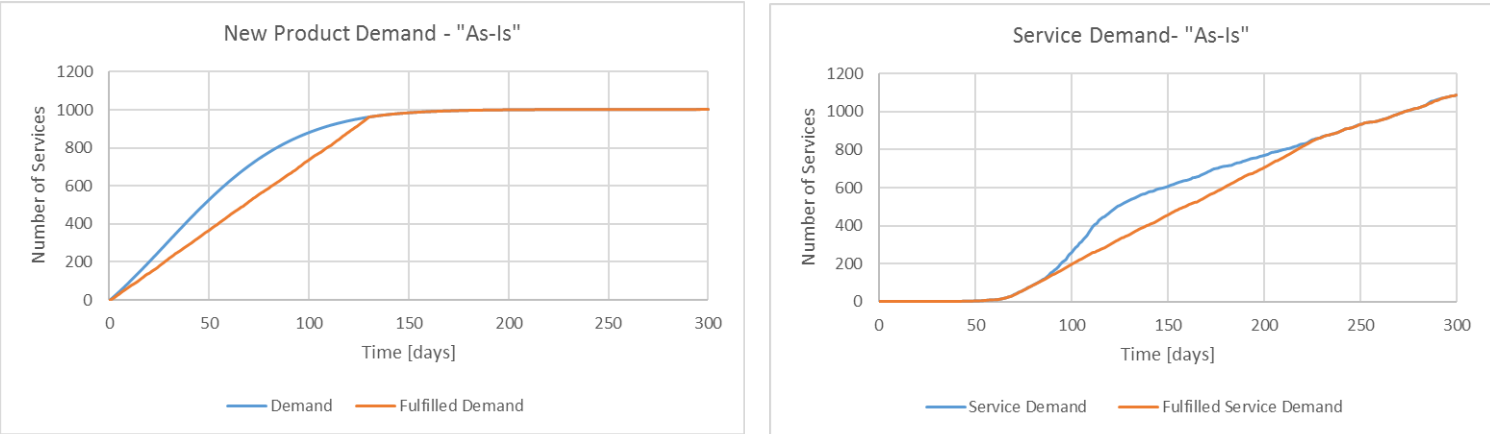

Figure 19 Dynamic response to customer demand (“As-Is”) graph

As shown in the graph, the “new product demand” starts with an abrupt increase with the release of the product to the market, this demand cannot be fulfilled instantaneously by the system until its stabilisation. Something similar happens with the “service demand” (triggered by the AB Model).

This is probably due to the fabrication, service and transport capacities, showing that the designed equipment number may not be enough to satisfy the initial demand, despite being sufficient in for the stationary demand afterwards. The constant slope in the fulfilled demand evidences that the capacity has come to its limit.

5.1.2. “To-Be” Scenario

Figure 20 shows the accumulated product/service demand against the satisfied demand for the “to-be” scenario.

The graph indicates that in this case, the system can meet the demand instantaneously, being both curves adapted. This is because the transport has been practically abolished and the automation of the fabrication/service processes, which have reduced the response time and increased the capacity of the system.

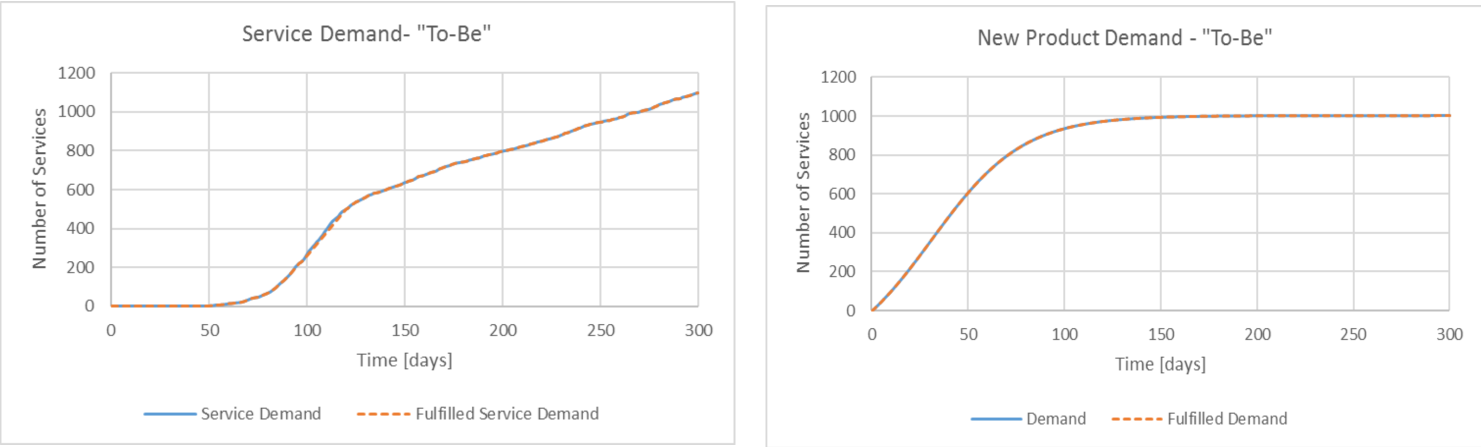

Figure 20 Dynamic response to customer demand ("To-Be") graph

The results provided by the simulation show that future RdM business model will ensure just in time manufacturing and increase the capacity enough to fulfil the customer demand with the same number of machines.

5.2. Cost-Revenue Analysis

5.2.1. "As-Is" Scenario

Figure 21 outlines the histogram for the costs and revenues of ShoeLab business model:

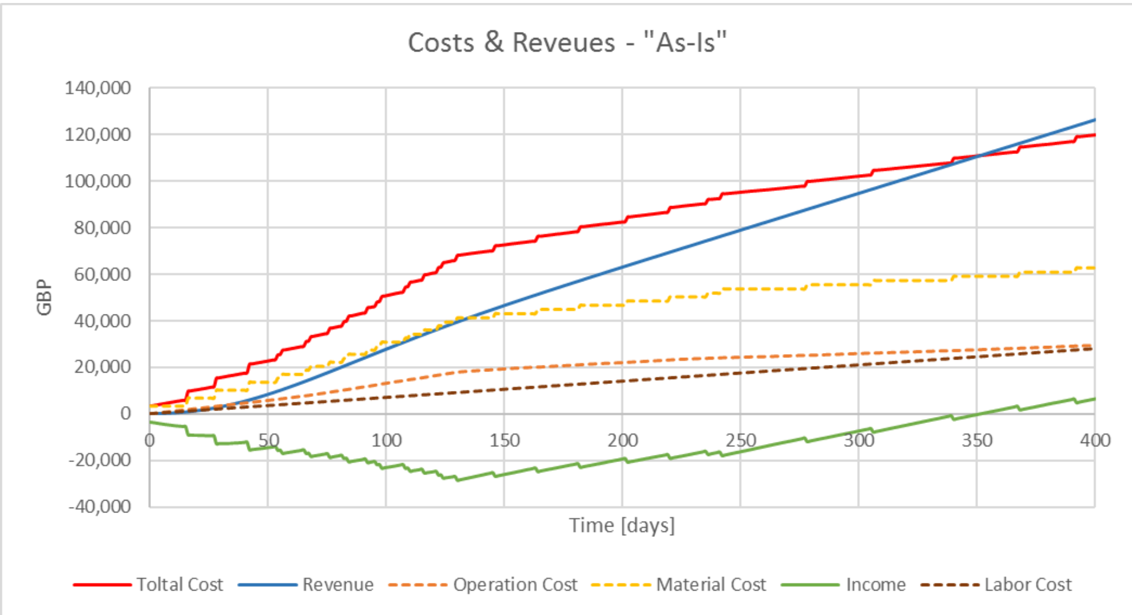

Figure 21 Cost-Revenue histogram ("As-Is")

As it is shown in the graph, the income after the launch of the PSS is negative. This is due to the payment method: the £15 monthly subscription is not enough to compensate the initial investment for manufacturing the shoes. However, this loss is mitigated with time during one year, until the revenues overpass the costs.

As mentioned above, the slope for the total costs is higher in the beginning, when the new customers start demanding their shoes. Once most of the "new product demand" has been fulfilled, the cost increase slows down, despite continuing growing due to the services provided.

Judging by these results, the business model would be profitable, given that the minimum subscription time is one year. This proves that providing the described services are affordable for the given subscription fee. Nevertheless, the profit margin for that time is minuscule and the risks might not be worth.

5.2.2. "To-Be" Scenario

Figure 22 outlines the histogram for the costs and revenues of ShoeLab business model:

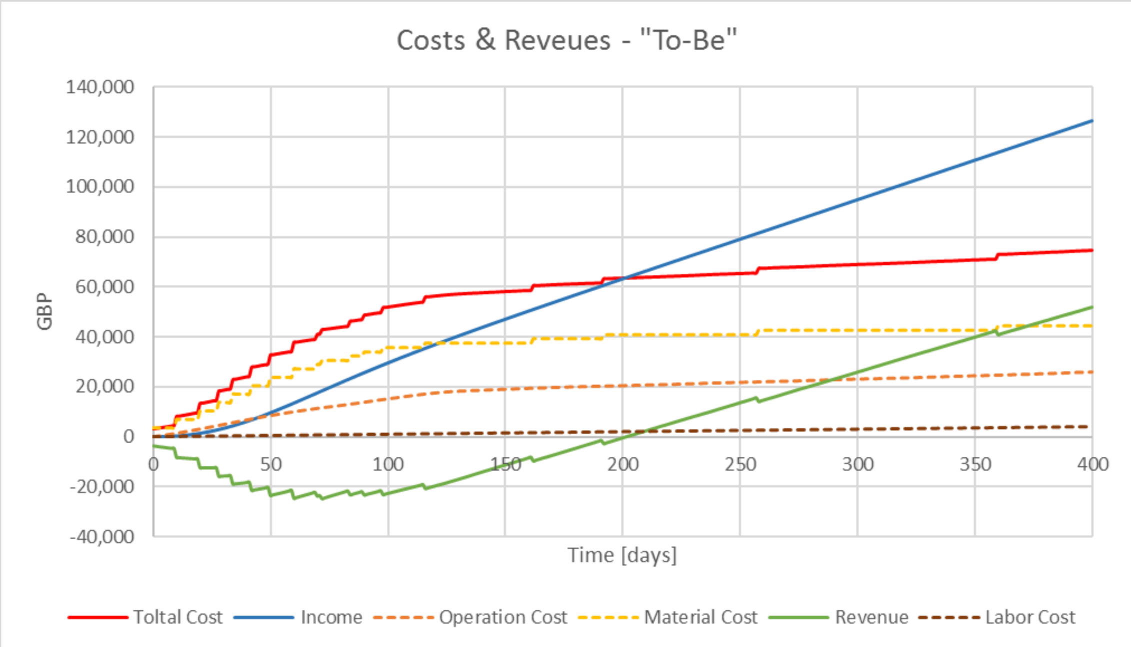

Figure 22 Cost-Revenue histogram ("To-Be")

The graph shows a significant reduction in the costs (40% off), which is explained one by one as follows:

- **Labour cost:** these costs are almost eliminated due to the processes automation, requiring just supervision and maintenance of the machines.
- **Material cost**: the recycling activities explain its reduction.
- **Operation cost**: these expenses are reduced because of the minimisation of transport and the automation of processes.

This improvement in costings advances the time to start getting incomes from the business (210 days), making sure that the business model is profitable and increasing the profit margin considerably. The output of the simulation, again, is spotting potential benefits for future RdM, giving quantitative figures regarding cost savings and income improvements.

6. Discussions and Conclusions

6.1. Contributions

This project has now successfully presented the SD modelling based on the case study reflected throughout the thesis, demonstrating the high-level design of the system. The objectives given in section 1.3 have been achieved: objective 1 was met by identifying ShoeLab as a RdM model; objective 2 has been met, provided that the simulation described section in 4 has enabled dynamic visualisation of the case study; data-driven decisions were used to set up and compare different RdM scenarios as shown in sections 4.5 and 5, meeting objectives 3 and 4; lastly, objective 6 (model validation) was achieved as described in section 4.6.

This thesis will contribute to the roadmap of research of RECODE network. In particular, it will be part of the feasibility study titled “Digital Re-Distributed Manufacturing (RDM) Studio”, a 9-month feasibility study for RdM. The study represents the first successful attempt of applying System Dynamics Simulation to RdM. SD modelling has proven to be a useful tool for describing system interactions and provide data-driven experimentation to represent multiple scenarios and quantify the problem.

It has been shown how ShoeLab can benefit from this simulation. The tool makes a quantitative analysis that can be used to make recommendations and help them design their distribution network and production capabilities.

6.2. Limitations

The results obtained by the simulation models are subject to constraints:

- **Input parameters value based on assumptions:** To make comparisons, it was assumed that the technology was in maturity level, and most input parameters were just estimated by comparing with other cases. This makes obvious that the results obtained are not going to be precise, even though is still valuable to see trends and compare scenarios.
- **Macro Level Simulation:** SD modelling is known not to provide low-level information. Thus, many details that could affect the results may have been missed.
- **Future uncertainty:** “To-Be” scenario was designed based on assumptions about how future RdM could be, even though it is impossible to predict what the future is going to look.
- **Limited scenario generation:** Data-driven experimentation was not always able to predict certain scenarios i.e., traditional shoe manufacturing. This is because data modifications cannot describe changes in the value chain.

6.3. Future research

Future lines of study after this project are listed as follows:

- **Obtain real and precise values for input parameters.** The parameters used for the simulation have been estimated on thhhe basis of assumptions, hence the results are not accurate. A deep research in materials, 3D-printing, transportation costs, etc… could be able to improve the model.
- **Make recommendations for ShoeLab.** As well as for Digital RdM Studio Purposes, the model could be employed to make actual recommendations for ShoeLab business

model regarding capacity planning, inventory management and finance analysis. This would be able to provide real value for the business model.

- **Include risk analysis features in the model**. One of the main benefits of RdM is the risk reduction. However, this has not been reflected in this study. Collecting enough information about the supply chain, transport and finance figures; a risk assessment of the system and its future improvement could be performed. A Montecarlo analysis would evaluate the resilience of different scenarios.

6.4. Concluding remarks

- It has been created a reliable SD simulation model that enables data-driven experimentation for RdM. To build the model, it was necessary to identify the primary constraints and elements that were going to be relevant to simulate a manufacturing environment. This task has been completed successfully because the tool enables modifying input parameters that have an impact and provide sensible results.
- Data driven decisions have been used to simulate different RdM scenarios. To develop the "to-be" scenario, it has been necessary to select the main parameters whose change could predict the future of RdM.
- The model shows how RdM will help future manufacturing. The simulation and comparison between the current and the future scenario show promising results: moving towards a more RdM environment will contribute to cost savings and capacity improvements.
- ShoeLab has been identified as a RdM business model and has been employed as a case study for the simulation. SD simulation model has succeeded to describe the ShoeLab environment, representing its value chain and connections.
- Simulation has shown the profitability of ShoeLab as a PSS. Computing the balance between cost and revenues, it has been demonstrated that, for the given input values, it is affordable to provide the product and services to the client for the given subscription fee.
- The SD model will help to quantify the problem and make recommendations for ShoeLab. Acquiring more reliable input data would contribute to having an accurate model that could provide valuable information in terms of capacity planning, inventory management and finance analysis.
- An AB Model has been built to predict the customer's behaviour. This model has implemented the client segregation and can predict the demand for any different type of client using statecharts. The combination of an SD and AB modelling has been successful.

Bibliography

Al-debei, M.M. (2008) 'Defining the Business Model in the New World of Digital Business', *Proc AMICS 2008*, (2000), pp. 1–11.

Baines, T.S. et al. (2007) 'State-of-the-art in product-service systems', *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 221(10), pp. 1543–1552.

CRO Forum (2015) '*The Smart Factory – Risk Management Perspectives*', (October), pp. 1–17.

Dauner, G. and Löbig, T. (2014) '*Business model transformation in the manufacturing industry*.'

Ellen MacArthur Foundation (2015) '*Towards a Circular Economy: Business Rationale for an Accelerated Transition*.'

Ellen McArthur Foundation (n.d.) '*Circular Economy Overview*'

Fayoumi, A. (2016) 'Ecosystem-inspired enterprise modelling framework for collaborative and networked manufacturing systems', *Computers in Industry*, 80 Elsevier B.V., pp. 54–68.

Ford, S. and Minshall, T. (2015) '*Defining the Research Agenda for 3D Printing-Enabled Re-distributed Manufacturing*'

Helo, P. et al. (2014) 'Toward a cloud-based manufacturing execution system for distributed manufacturing', *Computers in Industry*, 65(4) Elsevier B.V., pp. 646–656.

Kuijken, B. et al. (2016) 'Effective product-service systems: A value-based framework', *Industrial Marketing Management*, Elsevier Inc.

Lee, S. et al. (2016) 'When is servitization a profitable competitive strategy?', *International Journal of Production Economics*, 173, pp. 43–53.

Li, C. et al. (2016) 'A system dynamics simulation model of chemical supply chain transportation risk management systems', *Computers & Chemical Engineering*, 89 Elsevier Ltd, pp. 71–83.

Lieder, M. and Rashid, A. (2016) 'Towards circular economy implementation: A comprehensive review in context of manufacturing industry', *Journal of Cleaner Production*, 115 Elsevier Ltd, pp. 36–51.

Logility (2016) *Consumer Goods Business Issues*.

McLean, C. and Riddick, F. (2000) 'Simulation in the International IMS MISSION Project: The IMS MISSION Architecture for Distributed Manufacturing Simulation', *Proceedings of the 32Nd Conference on Winter Simulation*, (January 2000), pp. 1539–1548.

Melorose et al., J. (2001) '*Final Report from MISSION Project*'

Moreno, M. and Charnley, F. (2015) '*Can re-distributed manufacturing and digital intelligence enable a regenerative economy ? An integrative literature review*'

Nylund, H. and Andersson, P.H. (2010) 'Simulation of service-oriented and distributed manufacturing systems', *Robotics and Computer-Integrated Manufacturing*, 26(6) Elsevier, pp. 622–628.

Oracle (2016a) '*Solving the real challenges in the Consumer Goods Industry*'

Oracle (2016b) '*Information Age Applications for Consumer Goods*'

Preston, F. (2012) 'A Global Redesign? Shaping the Circular Economy', *Energy, Environment and Resource Governance*, (March), pp. 1–20.

Rüßmann, M. and Lorenz, M. (2015) '*Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries*'

Sendler, U. (2013) 'Industrie 4.0', *Beherrschung der industriellen Komplexität mit SysLM*, , p. Online–Ressource (XII, 144 S. 71 Abb, online resou.

Shimomura, Y. et al. (2014) 'State-of-art Product-Service Systems in Japan - The latest Japanese Product-Service Systems developments', *Procedia CIRP*., Vol.16, pp. 15–20.

Solereview (2016) *What does it cost to make a running shoe?*.

The Government Office for Science (2013) '*The Future of Manufacturing: A new era of opportunity and challenge for the UK*', , pp. 1–20.

Tonus, S. (2014) '*Product-Service System Desin*',

Uygun, Ö. et al. (2009) 'Scenario based distributed manufacturing simulation using HLA technologies', *Information Sciences*, 179(10) Elsevier Inc., pp. 1533–1541.

Witjes, S. and Lozano, R. (2016) 'Resources , Conservation and Recycling Towards a more Circular Economy : Proposing a framework linking sustainable public procurement and sustainable business models', *Resources, Conservation & Recycling*, 112 Elsevier B.V., pp. 37–44.

Wood, S. and Wang, C. (2013) 'The Future of Standards in the Consumer Goods & Retail Industry', *Capgemini Consulting*, , pp. 1–24.

Yearworth, M. (2014) '*A Brief Introduction to System Dynamics Modelling*', (October), pp. 1–15.

Appendix

List of model input parameters

Input parameters	
Name	Value
Advertisement Effectiveness	0.009
Adoption Fraction	0.15
Batch Size	200
Daily Salary	10
Equipment Capacity	12
Number of Machines (Fabrication)	3
Elastomer Cost per Shoe	9
Revenue per Person per Day of Data sharing	0.005
Monthly Subscription Fee	15
Ops Cost: New Shoe	7
Number of Operators	7 → 1
Population Size	1000
Recycling Factor	0 → 0.7
Ops Cost: Repair	4
Ops Cost: Refashion	4
Ops Cost: Replace	4
Technology Cost per Shoe	8
Transport Capacity	25
Transport Cost per Item	1
Transport Necessary	True → False