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A Framework to Support a Simulation-Based Understanding of Digitalisation in Remanufacturing Operations

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Abstract:

Modelling and simulations are important in predicting the response and behavior of manufacturing shop-floor operations such as predictive maintenance in relation to the real-life operations. Thus, remanufacturing operations, an end-of-life operation focused on returning a “disassemble-able” product to a condition which is at least as new as the original specification, can be influenced by modelling and simulation.

While simulations have a limitation in their ability to enable real-time business decisions in environments of complexity due to costs and time required to build these models, remanufacturing operations in particular will benefit from the application of simulations. As remanufacturing is characterized by an uncertain nature of product returns, simulation modelling can be used to support the understanding of different methods from a real-time scenario context. With manufacturing digitalization, complexity in remanufacturing is further increased with more data produced as sensor-enabled products enter the remanufacturing shop-floor.

This paper investigates how modelling and simulation could be used to provide clarity to the digitalization of remanufacturing operations and proposes a framework to support simulation modelling for remanufacturing sensor-enabled products. Findings from the synthesis of a systematic literature review and five remanufacturing case studies reveal that system dynamics modelling has greater application to remanufacturing over other modelling techniques. Additionally, the importance of digitalisation across the six stages of

remanufacturing is expected to be similar and, as such, reduces medium term cost implications for remanufacturers looking to digitalise.

1 Introduction

Remanufacturing, as with other approaches to circular resource use such as product reuse, refurbishment and recycling [1] have been discussed in industry and academia for several decades, but have recently been popularized by policy think-tanks such as the Ellen MacArthur Foundation (EMF)[1]. Remanufacturing has its history in the automotive sector where it started in the 1920s [2], which saw automotive parts being remanufactured by third parties. Following this, other industries and particular product categories such as aerospace, rail, ink and toner cartridges, lifting and handling equipment [3] have become key areas where value recovery of used products has been accomplished through remanufacturing. In its early stages, remanufacturing was a strategy to recover value from used products by manufacturers driven by the motive of profitability [4]. Thus, manufacturers have proceeded to establish profitable remanufacturing business models. These include, Xerox, General Electric, Caterpillar, Navistar and Deere [5]. The toner cartridge remanufacturing program at Xerox, for instance, saved $200 million worth of material costs in five years [6]. Currently (and beyond profitability), remanufacturing has been argued as part of the solution to reduce resource consumption while retaining economic advancement [4]. According to the EMF, it decouples economic growth from environmental impact [7]. Following this, several papers have emphasized the link between remanufacturing and sustainability [8], [9], [10]. The United Nations Environmental Programme's IRP[2] [11] report on the circular economy makes this link evident, highlighting remanufacturing as one of the key circular approaches needed to redefine value for sustainable manufacturing.

The product remanufacturing process entails recovering used products at the component level where the product is disassembled, worn out parts are replaced with new ones, reassembled and then tested, with the durable parts being reused. Motivated by the fact that remanufacturing is energy-retentive, there has been substantial research to gain a better understanding of the remanufacturing process, as well as to realise more economic and environmental benefits from the process [12],[13], [14]. As a process, remanufacturing is subject to a number of challenges and uncertainties such as price fluctuation, stochastic demand and challenges related to the core (used product or its part) such as uncertain quality of returned used products, timing and quality [15]. The European Remanufacturing Network

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[1] The Ellen MacArthur Foundation, EMF, is a UK registered charity that focuses on re-thinking, re-designing and building a circular future through the framework of a circular economy (https://www.ellenmacarthurfoundation.org/).

[2] International Resource Panel

(ERN) from its survey of 188 European remanufacturers also highlights the challenge associated with a lack of accurate, timely and consistent product knowledge. Several literatures including [16], [17], [18], [19] have proposed simulation modelling (SM) and analysis as a means to gain insight into manufacturing and remanufacturing, predicting the behavior of the remanufacturing and manufacturing shop floor operations in order to suggest solutions from real-time analysis. Historically, simulation modelling has been applied to different sectors beyond manufacturing. These include the service industry, healthcare, defence and the public services [16]. Simulation modelling techniques have developed and transformed by the evolution of the computer which has enabled the uptake of practical simulation tools and techniques [16]. Discrete Event Simulation (DES), System Dynamics (SD) and Agent-Based Simulation (ABS) also called Agent-Based Modelling (ABM) are commonly deployed simulation techniques used to support manufacturing decisions. Their deployment (also described as *suitability* or *appropriateness* and *relevance* [16]) in manufacturing have been argued to depend on levels of abstraction and availability of data as indicated in Figure 1.

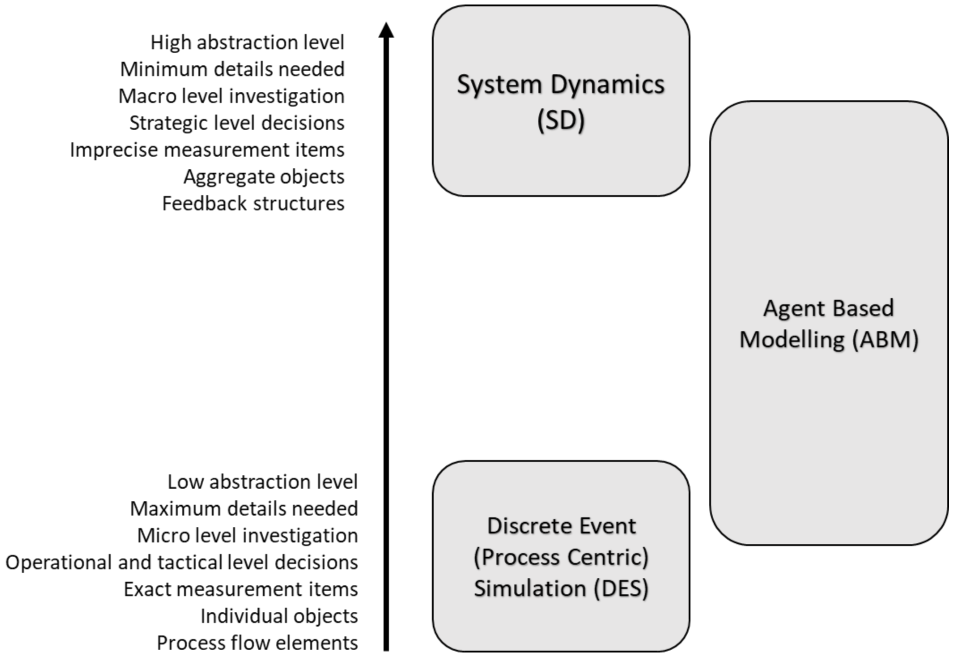

Figure 1: Abstraction levels for the simulation modelling methods (adapted from Borshchev, [20]**)**

In a study undertaken almost 10 years ago (Jahangirian et al. [16]), it was identified that these three simulation approaches were the most widely used in operational research (OR) for modelling business problems, amongst all other simulation approaches. Asides being used as stand-alone SM tools, Jahangirian et al. [16] and later Brailsford et al. [17] noted the increasing interest in hybrid simulation (defined as models that combine at least two of these three approaches).

As mentioned, research on simulation modelling exists in the area of manufacturing, operational research and business models. The integration of Industry 4.0 paradigms and manufacturing presents a unique development for the remanufacturing. Industry 4.0 (I4.0) (also known as the Fourth Industrial Revolution or Smart Manufacturing) is based on manufacturing systems driven by information technology [21]. Accordingly, it involves a combination of smart factories, smart products and the Internet of Things and is focused on providing real time information on production and processes, flow of components, machines, etc, thereby enabling better decision-making and visibility of the manufacturing system. Digitalisation of remanufacturing will hence involve the use of I4.0 paradigms for the six processes that constitute remanufacturing [22]. The aim of this paper is to develop a framework which can support the use of simulation modelling for a digitalised remanufacturing set-up through the use of a systematic literature review evaluation. It asks the research question: how can simulation modelling techniques identified from a systematic review of literature support a framework for simulation modelling in the digitalisation of remanufacturing operations? Thereafter future research in the area of simulation modelling for data-driven remanufacturing shall be proposed.

This paper shall proceed as follows: Section 2 describes the systematic approach to the literature search and highlights how the framework was developed. Section 3 presents the broad findings synthesized from the review of literature. Section 4 develops and validates the framework to support a simulation-based understanding of digitalisation of manufacturing operations. In the concluding Section 5, a reflection and discussion of the findings is presented along with the expected future work in this area.

2 Research Methodology

2.1 Simulation Modelling in Remanufacturing

The Centre for Remanufacturing and Reuse (CRR) describes remanufacturing as a “series of manufacturing steps which are applied to an end-of-use part or product in order to return it to like-new or better performance, with a warranty to match”, [23]. Steinhipher [24] lists the key steps of remanufacturing mechanical, electromechanical and mechatronic products to include disassembly, cleaning, inspection, reconditioning, reassembly and final testing/inspecting (Figure 2). Remanufacturing has been found to be more profitable than traditional manufacturing, offer critical information for product design through failure mode information, require less energy and natural resources and provide customers with the opportunity to obtain high-quality products at low prices.

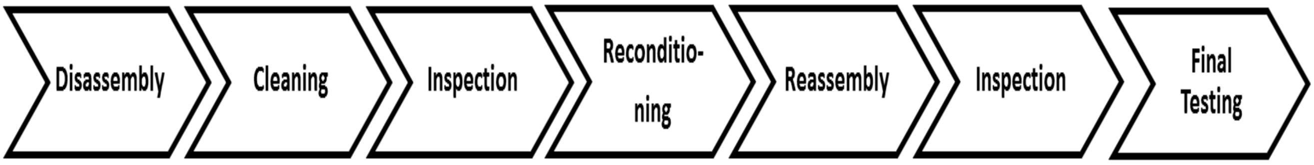

Figure 2: ***A generic remanufacturing process chart, based on the steps described in Steinhipher*** [24]

Owing to the increasing process complexity, new parts production and other remanufacturing challenges as highlighted in section 1, research shows that remanufacturing companies react passively to this complexity [25]. I4.0 intervention in manufacturing, which has seen a high level of automation through the adoption of ubiquitous information and communication technologies (ICTs), is expected to impact remanufacturing in terms of skill and technology challenges, sensorised machines for intelligent machining, and lifecycle design awareness [26]. As remanufacturing is primarily driven by the relationship between the original equipment manufacturer (OEM) and the third party remanufacturer (TPR), the uptake of I4.0 by the OEM is expected to affect remanufacturing and slowly drive remanufacturing towards end-to-end digitalisation of the physical assets and the entire supply chain [27]. Butzer et al [28] describe this as *remanufacturing 4.0.*

Simulation modelling has been suggested as a method needed to assess and improve remanufacturing processes and production systems [29]. It involves the development and analysis of models that imitate the behavior of the system being analyzed [30]. According to Pegden et al., [31] a simulation model can be used primarily for the following three purposes:

a. Analysis of system behavior,
b. Development of theories and/ or hypothesis based on observed behavior,
c. Prediction of future behavior.

A wide variety of simulation techniques and methods exist in practice and in literature. These include General-Purpose Simulation Languages, ABS, Monte Carlo Simulation, Bespoke programming, Petri-nets, Business games and Process Mapping [16]. However, System Dynamics, Agent Based Simulation and Discrete Event Simulation are amongst the most commonly used in practice as concluded in a review of simulation applications in manufacturing and business [16]. Thus, the first research question is proposed as:

Research Question 1

What are the most common simulation modelling tools used in remanufacturing?

The systematic literature review (SLR) phase as described in Tranfield et al. [32] is deployed to answer this research question. The SLR has been argued to support detailed research which takes into consideration any broad foundation as well as being able to achieve evidence-informed reviews and decisions. For the review SCOPUS and Web of Science (WoS) are used according to the literature review protocol as described in **Table 1.**

Table 1. Literature Review Protocol

Item	Description
Time Period	January 2000 to May 2019 (Search was performed in May, 2019)
Boolean Operators	AND between keywords; OR between Database search fields.
Search fields	“Remanufactur*, “System Dynamics”, “Discrete Event Simulation”, “Agent Based Simulation” OR “Agent Based Model*”
Language	English
Availability	Articles available online as full text
Research Discipline	Engineering; Business; the Sciences excluding Medical Science.
Exclusion Criteria	Articles unrelated to search words;
Publication type	Peer-reviewed academic journals; conference papers.

The review process conducted in SCOPUS and WoS is described in Figure 3. The database (SCOPUS and WoS) were selected as these have been proven to have more relevant literature for engineering and science across all available databases [33]. The literature review time period and language are defined in terms of their relevance to the study. The articles are excluded based on their discipline, relation to search words and publication type as mentioned in Table 1.

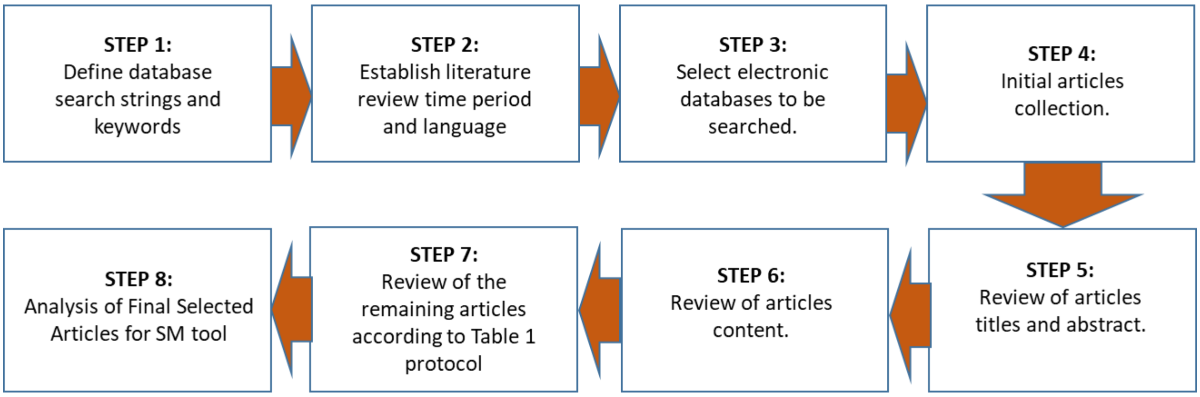

Figure 3: Flow diagram indicating the review process (Adapted from Okorie et al., [1])

2.2 Case Studies

In order to understand the digitalisation of remanufacturing operations, the second research question is proposed:

Research Question 2:

To what degree, if any, can remanufacturing operations be digitalised?

A qualitative, case study approach was employed in order to answer this question. The "case" has been described as the group, individual, organisation or situation which is being investigated by the researcher [34]. However, according to Yin [35], case study research is a research option "which involves an empirical investigation or a particular contemporary phenomenon within its real life context using multiple sources of evidence".

In this research, the case studies involved five automotive remanufacturing and manufacturing organisations which are based in the United Kingdom. The automotive companies were selected from the database, Conseil Europeen de Remanufacture[3] (www.remancouncil.eu). They are represented by respondents who have a deep experience of the remanufacturing industry and practice, which is important as remanufacturing is a process that relies on experienced knowledge. The profiles of these case study companies are given in Table 2.

Semi-structured interviews, based on findings from the literature review, were carried out with each of the 8 respondents. They were asked to give their opinion on the digitalisation of the remanufacturing stages as listed in the remanufacturing process chart in Figure 2. All respondents requested to remain anonymous and are hence designated as respondents A-H. Their responses are tabulated and presented in the next section.

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[3] The European Remanufacturing Council is a body representing small and large businesses from all remanufactured product sectors. Working with the European Commission and all EU member states, the CER has the vision of tripling the value of Europe's remanufacturing sector to €100 billion by 2030 and, as such, work with a good number of remanufacturers in the EU.

Table 2: **Remanufacturing Profiles of Case Study Companies**

Firm	Main Products	Reman (Type)	Interviewees (Years of Exp.)	Years of Reman Experience	Key Notes
Company A	Mechanical and pneumatic components.	OEM & Independent Reman.	**(A)** Managing Director (33); **(B)** Remanufacturing Sales & Parts Specialist (5); **(C)** Head of Remanufacturing (13).	45	Strong knowledge and commitment towards a Circular Economy.
Company B	Research in Digital Manufacturing	Reman. Research	**(D)** Manager, Circular Economy and Digital Manufacturing (6)	3	Performs other CE related research.
Company C	Hydrogen-powered fuel cell vehicle manufacturer	OEM	**(E)** Systems and Sustainability Engineer (5); **(F)** Systems & Software architect (6)	11	Possesses CE initiatives which focuses on CE opportunities in China, creating a value network with suppliers to service the supply chain, etc.
Company D	Auto (Electric) Remanufacturer	Independent Reman	**(G)** Managing Director (29)	32	Awarded the Green Apple Environmental Award.
Company E	Automotive Manufacturer (OEM)	OEM & OER	**(H)** Lead Engineer (15)	10	Strong on sustainability initiatives which includes a stand-alone sustainability unit.

3. FINDINGS.

The findings from the synthesis of the systematic literature review and five case studies are presented in this section. Interest in simulation modelling has grown rapidly since 2010 as can be seen from the growing numbers in the Winter Simulation Conference, which is the leading international conference on simulation [17]. Despite this evidenced uptake in research, it can be argued that simulation modelling in remanufacturing operations are yet to experience the same growth as observed in Table 3. The total number of papers on simulation modelling in the years under review (2000 – 2019) were 112 and 69 for SCOPUS and WoS databases respectively.

Table 3: Research Papers on Remanufacturing and Simulation Modelling Tools.

Database	"System Dynamics"	"Discrete Event Simulat*"	"Agent Based Simulat* /"Agent Based Model*"	"Hybrid Simulat*"
SCOPUS "Remanufactur*"	74	24	11	3
Web of Science "Remanufactur*"	40	16	10	3

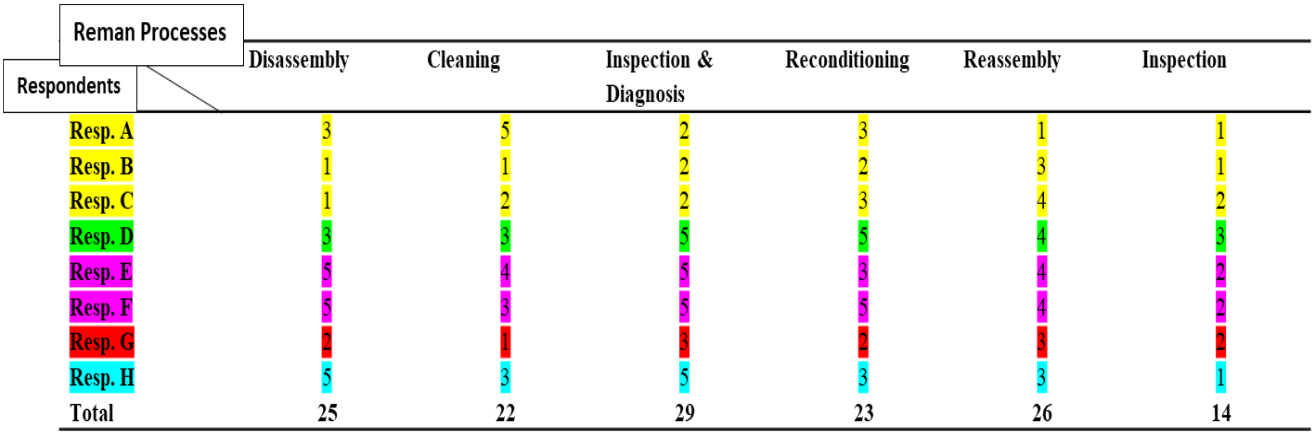
System Dynamics (SD) is used for modelling events that happen continuously (for example, machine deterioration). It is ideally designed for long-term, chronic, and dynamic management problems. This requires a high level of abstraction, macro-level investigation with minimum details needed [20]. According to Vlachos et al., [36], SD focuses on how the physical processes, information flows and managerial policies interact so as to create the dynamics of the variables of interest. These "managerial policies" refer to the long-term, macro-level decision rules which are driven by upper management. This finds application within remanufacturing. While remanufacturing operations can be modelled using DES or a hybrid SD-DES model, much of the decision-making in remanufacturing is led by stakeholders or the upper management whose extensive experience in remanufacturing is important for remanufacturing operations. This may inform the reasons the SD simulation modelling tool ranks highly amongst SM tools on SCOPUS and WoS. In addition, SD is expected to be useful for I4.0 integration with remanufacturing.

Semi-structured interviews were carried out with eight respondents from the 5 case study companies as listed in Table 2. The discussions, which lasted for 45 minutes each and by phone and WebEx, were conducted as driven by the following open-ended questions:

i. What do you think data-enabled remanufacturing would consist of?
ii. How will you rate the importance of simulation modelling in remanufacturing?
iii. How should simulation modelling be applied to remanufacturing operations –across individual stages or across the whole remanufacturing shop-floor operations?
iv. Can digital technologies be remanufactured? Can digitisation enable remanufacturing?
v. Current remanufacturing processes can be sub-divided into six. These are disassembly, cleaning, inspection & diagnosis, reconditioning, reassembly and final inspection. Where will these be ranked in order of impact of digitisation, if they are ranked 1 to 5? [1 = Very Low, 2= Low, 3 = Medium, 4 = High, 5 = Very High]
vi. How would digitisation in remanufacturing affect current remanufacturing operations and resources?
vii. What will you consider to be "digital intelligence" in remanufacturing? How can simulation modelling support "digital intelligence" in remanufacturing?

Their responses are presented in Table 4 below.

Table 4: Remanufacturing Stages and Level of Digitalisation.



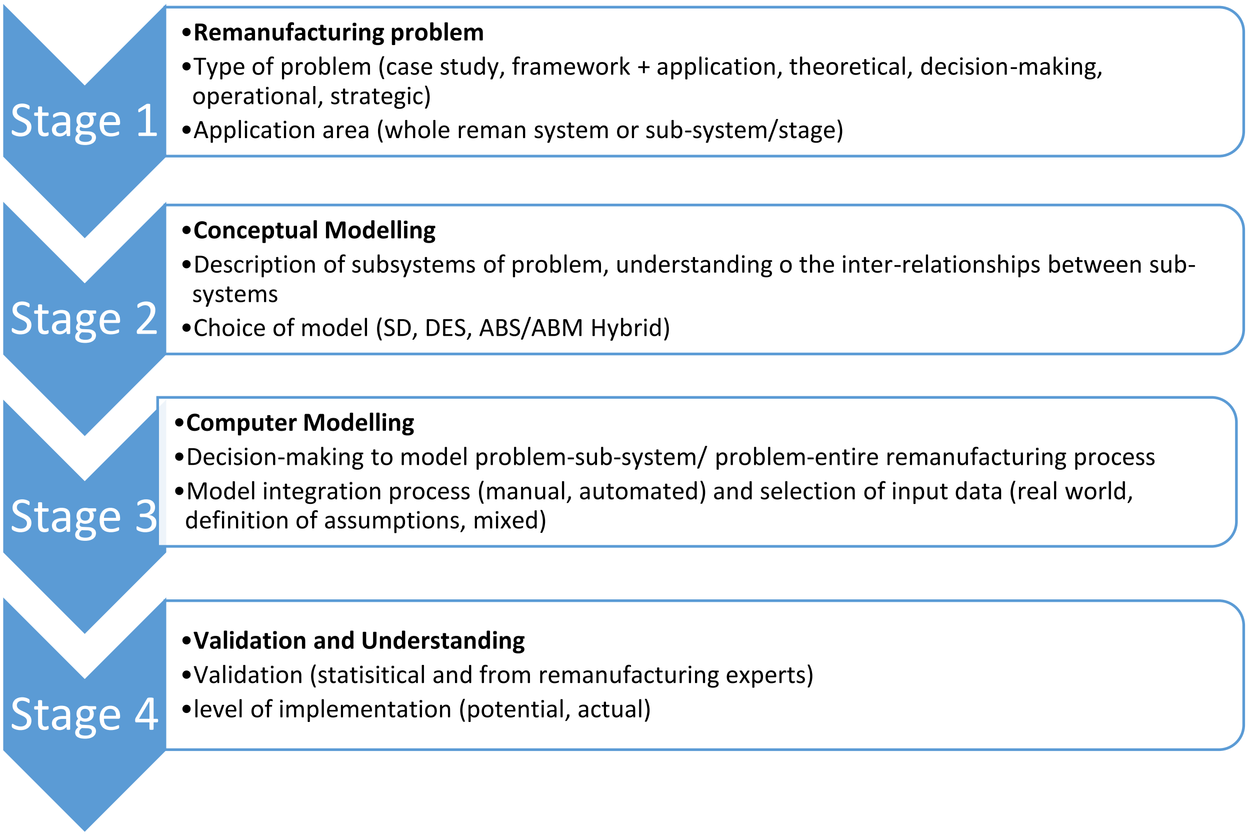
Reman Processes / Respondents	Disassembly	Cleaning	Inspection & Diagnosis	Reconditioning	Reassembly	Inspection
Resp. A	3	5	2	3	1	1
Resp. B	1	1	2	2	3	1
Resp. C	1	2	2	3	4	2
Resp. D	3	3	5	5	4	3
Resp. E	5	4	5	3	4	2
Resp. F	5	3	5	5	4	2
Resp. G	2	1	3	2	3	2
Resp. H	5	3	5	3	3	1
Total	25	22	29	23	26	14

**Color coding indicates the company for the respondents.*

From Table 4, it is evident that while remanufacturers expect different levels of digitalisation for each remanufacturing stage, these levels are not expected to differ widely. Thus, the cost of adoption of I4.0 paradigms in remanufacturing is not expected to be high as similar tools, resources, and processes across the 6 different stages of remanufacturing are expected to be the same. Respondents agree that the final inspection, where the re-assembled remanufactured product is checked for any defect and compared with the manufacturer's product specification, is expected to be largely a manual process. Hence, there will still be significant support from experienced resources.

4. FRAMEWORK FOR SUPPORT

Within this section a framework to support a simulation-based understanding for digitalisation in remanufacturing is presented. This framework (figure 4.) follows the understanding that all three SM methods have a recognised set of steps for model development [17], system dynamics simulation modelling technique has been applied to remanufacturing more frequently in comparison to other SM techniques in literature, digitalisation of remanufacturing operations is expected to be fairly similar across existing stages and the understanding that human experience will still be important for digitalisation in remanufacturing operations. This framework is modelled according to the framework for hybrid simulation in Brailsford et al. [17] and from the responses of respondents to the questions in Section 3.



- **Remanufacturing problem**
- Type of problem (case study, framework + application, theoretical, decision-making, operational, strategic)
- Application area (whole reman system or sub-system/stage)

- **Conceptual Modelling**
- Description of subsystems of problem, understanding o the inter-relationships between sub-systems
- Choice of model (SD, DES, ABS/ABM Hybrid)

- **Computer Modelling**
- Decision-making to model problem-sub-system/ problem-entire remanufacturing process
- Model integration process (manual, automated) and selection of input data (real world, definition of assumptions, mixed)

- **Validation and Understanding**
- Validation (statisitical and from remanufacturing experts)
- level of implementation (potential, actual)

Figure 4: Framework to support a simulation-based understanding of digitalisation in remanufacturing.

Validation of this framework was done by presenting the framework to the interview respondents from which their respective feedback was sought. Respondents broadly agreed that this represents a good base framework for simulation modelling to support the uptake of digitalisation in remanufacturing. Respondents, however, urged that the framework should be modularised and expanded to “micro” operational-level models and “macro” whole-system or aggregate SD models which, according to [17], takes a more strategic view of remanufacturing. Operational and strategic understanding of existing simulation frameworks for manufacturing operations in order to understand better (and possibly modularize) this framework was also suggested by respondents.

5. CONCLUSIONS

This paper has explored the potential of using simulation modelling to support the uptake of digitisation in remanufacturing operations. A framework to enable digitalisation of remanufacturing operations was presented. This framework model followed the systematic literature review of existing simulation modelling in remanufacturing papers as well as semi-structured interviews with 5 identified case study companies. The model details the process that should be followed for using SM to support digitalisation uptake amongst remanufacturers. From this research, it is important to consider the type of simulation tool as well as the stage for which it will be applied.

The model assumes that remanufacturing will be influenced by the technical and managerial views of remanufacturers. It also assumes that at least one SM modelling type will be applicable to the remanufacturing process. This research has shown that the uptake of digitalisation across the remanufacturing operations is not expected to have a wide variation. This reduces an adverse medium and long-term cost implications for remanufacturers willing to digitalise their operations using applicable I4.0 paradigms. This research has also shown that experience in remanufacturing will largely continue to be needed as remanufacturers digitalise. Thus, the advantage of remanufacturing being “labour-intensive and economically viable” is expected to continue.

Future work in this research area will include implementing SM modelling to an existing remanufacturing line. As adoption of applicable I4.0 paradigms has advanced in manufacturing, future studies could include applying the SM learning from manufacturing to remanufacturing.

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