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A multi-method simulation approach for evaluating the effect of the interaction of customer behaviour and enterprise strategy on economic viability of remanufacturing

Aydin Nassehi (2)[a,*], Marcello Colledani (2)[b]

[a] Department of Mechanical Engineering, University of Bristol, Queen's Building, University Walk, Bristol BS8 1TR, UK
[b] Politecnico di Milano, Department of Mechanical Engineering, Via la Masa 1, 20156 Milan, Italy

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ABSTRACT

The economic viability of remanufacturing is shown to be significantly affected by the interaction between customer behaviour and strategic decisions of the manufacturer. The paper investigates this interaction using a multi-method simulation model combining a multi-agent-based model of customers and a system dynamics based model of the remanufacturing enterprise. The model uses validated approaches for each component and is used to investigate, analyse and forecast the long-term effects of strategic decisions of the remanufacturing enterprise on customer behaviour and the consequent effects on the business environment that determine the profitability of the enterprise.

1. Introduction

Remanufacturing is widely recognized among the most profitable and resource efficient options for implementing the circular economy paradigm at industrial level, since it targets the recovery and reuse of functions and materials from post use-products [1]. It is defined as the set of operations for returning a used product to, at least, its original performance with a warranty that is equivalent or better than that of the newly manufactured product [2]. The benefits of remanufacturing are particularly relevant in the scenario where the manufacturer exploits its product knowledge to offer a remanufactured product to the aftermarket, at more affordable economic conditions.

A typical example of this scenario is the automotive industry, where the aftermarket volumes create significant business opportunities for remanufacturing. In spite of the business attractiveness of remanufacturing and the growing interest towards circular economy, making a transition to new remanufacturing businesses is perceived as a high-risk opportunity for manufacturers, mainly due to the significant sources of uncertainty and the relatively long-term horizon of profit returns. Uncertainties mainly relate to the accessible post-use volumes, the post-use product conditions, the technical dismantling aspects as well as the customers' acceptance of remanufactured products, which strongly affect the remanufacturing system profitability. As a consequence, capturing the dynamics and inter-dependence of these variables over time and their mutual effect on the effectiveness of remanufacturing decisions into a comprehensive model would be a fundamental asset for manufacturers in their transition to sustainable remanufacturing businesses, ultimately boosting circular economy at large scale.

This paper proposes a novel approach for assessing the interaction of parameters that affects production systems at different points in the product lifecycle and shows the effective application of this approach to remanufacturing where the insight can be used for effective investment strategy setting [3]. The proposed approach is based on multi-method simulation and combines the versatility and fidelity of agent-based simulation with the strategic acuity granted by system dynamics.

Traditionally, simulation in manufacturing systems is carried out using one of the three fundamental methods, namely Discrete Events Simulation, System Dynamics and Agent Based Simulation [4]. These methods have been individually applied across the lifecycle of manufacturing and remanufacturing systems but little work has been carried out in simulation of interactions between system variables across different phases of the later stages of the lifecycle, in a dynamic manner [5] with the notable exception of the work carried out by Umeda et al. who mainly focused on environmental analysis and product design [6]. The challenge presented by such cross-phase interactions is that each of the individual approaches is suitable for modelling certain aspects of each phase. For example, system dynamics has been shown to be an excellent method for modelling and analysis of strategies and long-term policies and their effects on production. Agent based models, on the other hand, provide a framework for describing diverse behaviours. The decision mechanisms of customers can thus be captured with a much greater fidelity in agent-based modelling compared to other approaches.

Hence, none of these approaches can, in isolation, provide a good solution to simulate mutual interactions across different phases. A suitable alternative would be to combine multiple simulation approaches in a single framework to benefit from the advantages of

* Corresponding author.
E-mail address: aydin.nassehi@bristol.ac.uk (A. Nassehi).

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each approach for each phase in the lifecycle. The combination of system dynamics and discrete events methods is presented as hybrid simulation and is well explored in the literature but studies in remanufacturing combining agent-based techniques with the other two are rare [7].

In the remaining sections of the paper, the fundamentals of multi-method simulation are explored and the logic of system dynamics and agent-based modelling are explained to provide an overview of how the two are linked together. The proposed approach is applied to remanufacturing as a problem that spans multiple phases of the lifecycle. The resulting multi-method model is simulated to show how this approach can be used to analyse and forecast long-term interactions of variables in each phase of the system lifecycle. Finally, the results are used to draw conclusions about the applicability of the proposed approach to the circular economy.

2. Overview of the multi-method simulation approach

The proposed multi-method model for remanufacturing is based on the integration of system dynamics, modelling the strategic and operational aspects of the remanufacturing business scenario, and agent-based simulation, modelling the customer behaviour towards newly manufactured and remanufactured products. Their basic features are discussed in the next sections.

2.1. System dynamics (SD)

In *SD*, the system is described in terms of flows that are integrated in stocks. This results in formation of differential equations that are solved using numerical methods. There is a general assumption of continuity in the values of variables in this method, so sudden changes in variables can introduce simulation artefacts, fragile models and unreliable results. The methodology is good for observing trends over time rather than individual values. As a result, it is an excellent approach for modelling policies and assessing causes and long-term effects of parameter and structure changes. When applied to remanufacturing this method can provide a validated aggregate view of the production system without excessive detail [7].

2.2. Agent based modelling (ABM)

In *ABM*, the participating entities in the production system are modelled as distinct units that interact with each other, exchange messages and pursue their individual goals. Agents are independent software entities that are executed in parallel and generally reside in the same virtual space. Each agent can be given a set of goals to pursue. Multi-agent systems are thus difficult to control, basically due to emergent behaviour. Modelling using agents is appropriate when various behaviours are expected from the same type of entity. Multi-agent models are most powerful when the various entities communicate with each other; “messages” are used to model these interactions. Previous research has shown that this approach can be successfully used in modelling customer behaviour [8–10].

2.3. Combining the two models in a single framework

In order to effectively combine multi-agent simulation with system dynamics, there are two potential approaches: manipulate agent variables in the system dynamics model or vice versa. Manipulation of agent variables in the system dynamics model is difficult and will require elaborate coding of manipulations for each individual agent as well as potential introduction of non-continuous elements in the model that could lead to derivation difficulties. As a result, manipulation of system dynamics models by the agents is the more promising approach for linking the two methods. Care should be taken not to introduce discontinuities into the system. Anylogic, a Java based simulation software, provides an environment for multi-method simulation and allows the manipulations to be carried out in a computationally safe manner. It has thus been chosen to test the proposed approach.

3. Description of the model

3.1. Modelling the remanufacturing system

The system dynamics model in Fig. 1 is used to create a simple model of remanufacturing production systems without loss of generality; it is inspired by the method proposed in Ref. [8].

The main stocks in the model are: 1. the backlog of factory orders for remanufactured products (*RemanBacklog*) 2. the remanufactured stock that has been produced (*RemanProducedStock*); and, 3. the remanufacturing capacity of the factory (*Remanufacturing Capacity*). The remanufacturing production flow (*RemanProduction*) connects the backlog stock to the produced stock. The remanufacturing capacity is adjusted by the flow that represents the building of new facilities and hiring additional workforce (*CapacityBuilding*). Two parameters define the delays that exist in the dynamic system: *FactoryExpansionDelay* defines how long it will take the enterprise to increase the capacity by one production unit per time unit (which has been selected as weeks in this instance), *ManufacturingLeadTime* defines the time that it takes for a remanufactured product to be produced. It is assumed that product delivery is instantaneous. The decision variable representing the production policy is the stock coverage that the enterprise wishes to maintain: *TargetLeadTime* defines the length of time within which the enterprise would like to clear the backlog at any given time. A lower value for this variable would mean an increase in the capacity and hence lower work in progress but higher investment costs. A higher value would mean that customers will have to wait before they get their orders delivered. *TargetLeadTime* can, at best, be equal to *ManufacturingLeadTime* which is the time that it takes to physically perform all production steps in the remanufacturing process. Thus, the important aspects of the model can be mathematically summarised as:

$$RPS = \int \min\left(\frac{RB}{MLT}, RC\right) dt \quad (1)$$

where *RPS* is the remanufactured product stock, *RB* is the backlog of orders for remanufactured products, *MLT* is the manufactured lead times and *RC* is the remanufacturing capacity of the factory. The remanufacturing capacity expansion is modelled by:

$$RC = \int \max\left(\frac{\frac{RB}{TLT} - RC}{FED}, 0\right) dt \quad (2)$$

where *FED* is the time it takes for investment in capacity expansion to yield results and *TLT* is the target lead time decided by the enterprise strategy. This creates the simplest non-trivial example of a non-linear dynamics system to enable the effect of strategies to be modelled in the remanufacturing system. The assumption is that the remanufactured product is competing with a newly manufactured alternative. Whilst the manufacturing system of the alternative can be modelled in a similar manner, it may be assumed that its dynamics are well recognised, and a simple delay (*AltDelay*) can be used to approximate the alternative production system without loss of generality.

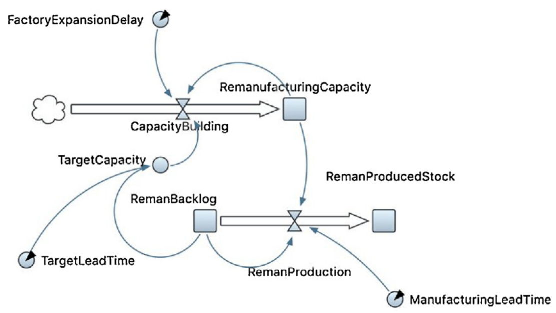

Fig. 1. System dynamics model of the remanufacturing system.

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