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A new method for simulation modelling of leaner remanufacturing in PaaS settings

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Abstract

The application of simulation technologies (STs) in the industry 4.0 paradigm can accelerate the implementation of the circular economy (CE) in companies by faster modeling and optimization of value retention processes (VRPs), such as remanufacturing or refurbishment. In business practices, the efficiency of the collection of used products and their recovery for a new or extended lifecycle is influenced by a high level of uncertainty. The product-as-a-service (PaaS) model might change the boundary conditions, which will decisively influence the operational factors such as time for a disassembly, and material recovery rate. The state-of-the-art in commercial simulation software (e.g., FlexSim, Simio, Arena) is based on the object-oriented approach, which requires that users must build the model themselves from a set of objects (object libraries), which is effective for a traditional linear process but is less suitable for multiple flow of a product between PaaS contracts. Remanufacturing in PaaS for consumer markets is currently a niche practice, due to the difficulties of providing its economic viability. Lean management practices are promising in lowering the cost of remanufacturing. The aim of this paper is to develop a new method for simulation modeling using a high-level script language, similar to those used by industry experts, according to lean remanufacturing principles under PaaS conditions. This novel method is built on the user-centric principle. Thus, it enables to build the simulation models and to use them by decision-makers in business practice who are not specialists in simulation modeling and do not have programming competences. The library of reference processes for remanufacturing in PaaS is defined with the industrial partners.

Keywords: circular economy; simulation modelling, design,

1. Introduction

Product-as-a-Service (PaaS) is an example of circular business model, in which the ownership of a product stays with a manufacturer/or PaaS provider, and customers pay subscription fee, or pay-per-use fee for access to products and/or their functions [1,2].

To achieve economic and environmental viability, PaaS providers engage in value retention processes (VRP), and reused, repaired, and remanufactured products or their components between multiple PaaS contracts [3]. PaaS is perceived to be one of the most effective instruments for improving environmental performance [4], and supporting efficiency in the use of critical raw materials (CRMs) [5].

The Product-as-a-Service (PaaS) model changes the boundary conditions for remanufacturing, as original equipment manufacturers (OEM) keep the ownership of products, thus can proactively manage the duration of the contracts an collect products from customers with sufficient residual value. As a result, the uncertainty of timing and amount of cores (used products) which are input for a remanufacturing process can be reduced [6].

Digital technologies can help optimize economic and environmental performance in PaaS, in particular supporting the most efficient remanufacturing of products [3]. They can

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significantly reduce decision-making time with regard to the moment of the collection of products from customers and enable simulating the optimal volumes of products needed for cost-efficient remanufacturing in PaaS. Digitally-enabled remanufacturing is crucial to provide the most efficient management of products in PaaS across multiple contracts [3,7,8]. Furthermore, simulation modeling has the potential to find the most suitable process organization to facilitate resource-efficient, leaner remanufacturing [9,10].

However, the available simulation technologies, primarily DES (Discrete Events Simulation) and ABS (Agent Based Simulation), require a high level of modeling and programming competencies (e.g., Anylogic – Java, FlexSim – FlexScript/C++) by potential users, which are not available at a company, or employing external DES and/or ABS specialists who have such competence.

This paper develops a new actionable method for simulation modeling of remanufacturing in PaaS using a high-level script language corresponding to the language of work used in business.

The novelty of the proposed approach results from the fact that we use an approach based on the language of work used by manufacturing engineers, production system designers This facilitates creating simulation models and digital twins of factories using the language which is used in real world. On the contrary, the state of the art in commercial simulation software (e.g., FlexSim, Simio, Arena) is based on the object-oriented approach, which requires that users must build the model themselves from a set of objects (object libraries) and use abstracts to model logic.

The paper is organized as follows; the theoretical background and the problem definition is described in Section 2. The new approach based on language of work and multimodal approach is presented in Section 3. The application of the proposed approach for remanufacturing in PaaS is presented in Section 4. The final conclusions are stated in Section 5.

2. Theoretical background and problem definition

2.1. Specific PaaS conditions affecting remanufacturing and the resulting research challenges

In PaaS, OEMs can keep control over products in their usage phase and, thus, proactively manage their lifecycle. The control over products changes the boundary condition for a remanufacturing system, as allow for the management of the input flows. OEMs or PaaS providers gain knowledge about which products, when and in which amount will be returned. Furthermore, thanks to the digital technologies and related data from use phase, they obtain knowledge on the state of health (so-called core quality) [11]. These are preferable conditions compared to the traditional linear sales model and might significantly improve the effectiveness and resource-efficiency of remanufacturing. Therefore, remanufacturing in the PaaS context creates opportunities for new research.

In the case of PaaS, the uncertainty related to the quantity and availability of cores for remanufacturing is limited, as the

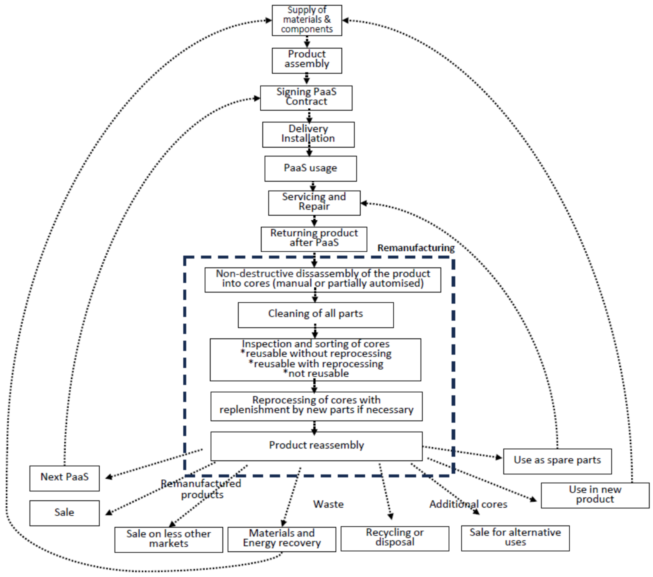

Figure 1. Flow of operation in PaaS process including remanufacturing phase

PaaS provider can proactively manage the duration of contract. The main source of uncertainty in remanufacturing in PaaS is related to the 'state of health' of a product (with inspection and disassembly to determine the suitability of the cores for remanufacturing). This type of uncertainty causes a variable sequence and variable duration of operations and must be addressed in a simulation model

Previous research has shown that the economic and environmental performance of the remanufacturing process can benefit from the implementation of lean management principles [12,13], such as:

- Implementing standard operations, instructions, or/and checklists;
- Implementing continuous flow;
- Elimination of unnecessary stock;
- Eliminating unnecessary waiting time for operations;
- Eliminating unnecessary transportations;
- Eliminating overproduction;
- Eliminating defects;
- Design of factory layout for continuous flow;
- Developing teamwork and employees cross-training.

The model design in the simulation software shall allow to monitor the one-piece flow of orders through the process and to eliminate non-value adding activities.

Simulation modelling of remanufacturing process is challenging, as a remanufacturing process can differ between products. The most generic stages of processes are: cores (used product's) collection/delivery, inspection, disassembly, cleaning, sorting, reprocessing, dispatching, reassembly, and final testing [14].

Studies on simulation in remanufacturing are limited. Most of existing studies apply the discrete event simulation approach to cope with remanufacturing uncertainties [10,15]. More complex approaches are rare. An example of more holistic approach, is the work of Goodall et al. [16], as they have proposed a data-driven approach that includes three elements: 1) an adaptive remanufacturing simulation algorithm for modeling of material flow in remanufacturing; 2) an information model; 3) a service layer to collect and analyze sensor data.

Silva Teixeira et al. [17] proposed a complex symbiotic simulation system (SSS) to support contract remanufacturers in managing service contract planning and execution. Furthermore, they linked the simulation model to the physical system.

Okorie et al. [7] compared system dynamics, discrete event simulation and agent based modelling techniques to identify to best tool for modeling of smart-remanufacturing. They concluded that new hybrid approaches are needed to address the challenges of remanufacturing. Weidmann et al. [18] have also identified Agent-Based Modeling (ABM), System Dynamics (SD) and Discrete Event (DE) Simulation, as appropriate methods for simulation of product as a service approach. They applied DE to forecast and evaluate different scenarios, but did not consider value retention processes.

To sum up, existing approaches are fragmented and they focus on the scheduling of the existing process, or data-driven approaches for existing process. The methods and tools which assist a company in remanufacturing in PaaS are missing.

Most of the commercial software for simulation are based on the Discrete Event Simulation (DES) paradigm. That allows for modeling of a dynamical system (taking into account changes in time) in which both the state variables and the mapping of the passage of time are discrete. When an event occurs in the system, specific actions related to that event are performed, and system statistics are recorded [19]. In discrete simulation, the basic concepts are as follows:

- object-oriented modeling,
- modelling with queue networks.

Object-oriented modeling maps the modeled reality onto a structure (diagram) that describes objects, their classes, their mutual connections, their behavior, and interaction.

Queue networks are graphs in which the vertices map job queues, service stations, and other resources of the system. Directed edges connect vertices and determine the execution of individual tasks. These tasks wait in queues for their start, which is conditioned by the availability of static system resources, which are called service stations. The literature shows that the traditional classical approach to discrete event simulation is object-oriented [20].

The basic assumptions of discrete simulation consist of:

- description of the system based on object-oriented modeling of dynamic and static elements of the system;
- individualization of system objects with the possibility of grouping them into classes, sets or by attributes;
- discretization of changes in the state of system objects carried out by means of mathematical discrete functions;
- discretization of the times of changes in system states according to the method of event succession or according to the step method;
- the simulation results are statistically aggregated characteristics of the system;
- The basis of the simulation algorithm is the course of discrete events that create activities and processes.

When a simulation model is built, the elements (called objects) reflect or approximate the real system.

Commercially available applications (Tecnomatix, FlexSim, Anylogic, Simio, etc.) are object-oriented programs that provide users with a set of objects and tools for creating flow logic (state diagrams, flow diagrams, etc.) that are used to 'force' objects to behave analogously as in a real life. Finally, to match objects, the user must master programming skills. Objects are developed in parallel (separately) with the tools that describe the logic of their flow. Building relationships between objects is left to users. Thus, users shall increase their modeling/programming competences which often are not required for the engineers responsible for remanufacturing operations, especially in the case of PaaS where products come back from multiple contracts in various technical states.

In practice, describing complex systems using an object-oriented approach might result in unreadable, incomprehensible, and unverified program code [16]. This is partly due to the cognitive gap between the abstractions offered by the languages and the complexity of the specifications, and the sometimes ill-defined semantics of programming languages, which makes it difficult to understand for users.

To scale up the remanufacturing in PaaS a more user-centric approach is needed to modeling, which is simple and actionable. The users (engineers/decision makers) are able to:

- Describe what needs to be done, while using the 'language related to technological operations and work routines, which is proactive and not abstract.
- To analyze and track the performance of work processes.
- To explain the phenomena which are happening in a real factory, without and avoid programming.

In our approach, we search for a description that is readable and understandable to engineers in the context of PaaS. The research questions are stated here as follows:

- How can simulation modeling support the design and organization of a remanufacturing in PaaS?
- How can we build a simulation approach for remanufacturing that automatically implements the principles of lean management?

3. The new approach using lean simulation language of work and multimodal approach

To address the uncertainties of process flow in remanufacturing in PaaS we apply a multimodal (cyclic) approach [15,19]. The multimodal process is carried out by (using) local cyclical processes. This approach allows to deal better with uncertainty inherent in routings and timing of operations. This also applies to the work of robots, means of transport, etc.

In a real remanufacturing facility, parts are moved in special containers (e.g., plastic bins or pallets), so in simulation approach we assume that a token is the container, and the flow is carried out by local cyclic processes. The flow of containers – tokens take place between locations. All technological operations are carried out at workstations (or equivalent unit) between locations. Then, a different picture emerges of the factory and its processes (flows). It is so called operations-based approach.

Adopting a solution based on the fact that the flow is carried out by operators carrying out cyclical processes. Then defining a high-level language in which the work routings of operators are described in a way identical way, as in a real factory. The instructions (operations) of this language correspond to the work instructions carried out at the workplace by the employee or robots. The construction of such a language makes it possible:

- identifying the start and end time of operations (work language instructions), which allows for creating Gantt charts of the operations being performed;
- assigning attributes to operations, which enables the performance of value-added activities (Lean management analysis).

In DES, the essence is the event and the reaction to this event. Whilst, in the proposed approach, the essence is the observation and implementation of the right routings (cycle). This corresponds to situations in a real factory. Work in a factory is carried out by workers, robots, automatons, etc., who have their principles of operation in the form of cycles (repetitive work). This is similar to the agent-based approach, but without social behavior. If operator observes an event, e.g., parts in the container have run out, or a failure has appeared, he/she reacts to it by switching to the appropriate response (an event handling cycle). In a real factory, operations are carried out by employees, robots, AGVs/AMRs, etc., in a defined space.

In the digital world, model developers do not have this awareness (knowledge). Classic DES simulation programs do not solve this situation. Orientation in space is part of the proposed approach. This means that an element of a high-level language instruction (operation) includes also information about the allocated space to perform it. An identifier for this object includes the X, Y, and Z coordinates with assigned meaning. Therefore, data on the topography of the factory (a layout with characteristic points) is crucial. Landmarks are identified and then given meaning with relations (mutual connections) between elements. The proposed approach adopts the following high-level language statement syntax:

- Where: - denotes the element of the supply chain/factory to which the activity relates,
- What: Activity - the name of the operation,
- How: Parameter.

The instructions are stored in tables. It is assumed that a set of such instructions in a single table (arranged in the order of their performance) corresponds to one routing (duty cycle) of an operator. If an operator has to perform many different jobs, described by different routings, these are saved in many tables. A change in work causes a change in the table (duty cycle) according to the multimodal approach. At the same time, the entry in the table is natural for the engineers in the factory. It also allows to structure the process, separating the executive level, the work cycle, from the control level, deciding what work is to be performed.

The instructions are related to:

- Traveling - Travel, TravelLoaded;
- Containers and locations - Load, Unlload, EmptyTote;
- Checking and Waiting – CheckPartInToteWait, CheckPartOnTableWait, CheckEmptyAreaWait, CheckFirstEmptyToteWait, CheckLocKanbanWait, CheckOneEmptyToteWait, CheckToteWait, WaitForFilledTote,
- Checking - CheckEmptyTote, CheckFilledTote, CheckLocKanban, CheckPartInToteCall, CheckToteCall, CheckToteKanban,
- Making: SetAssembly, Assembly, SetDisassembly, Disassembly, Welding, PushButton, Rework, QualityCheck, Wait, Work, etc.

Particularly important are the instructions that belong to the Checking, Waiting and Checking groups because they are used to address issues related to synchronization, coordination, and access to shared resources. In a real factory, when two employees approach the same location where, for example, one container with parts is located, the issue of simultaneous access to this container is solved naturally. Even if they come together at the same time, they notice that there is only one container, one of them will take the container first, and the other will withdraw from the action of picking the container, as it is no longer there. Later, he/she will either wait for this container to appear in a given location or move on to another job (switch to another cycle). In DES simulation programs, the whole situation has to be programmed using tools related to coordination and synchronization.

In the proposed approach, the mechanism for synchronizing and accessing shared resources is built into the high-level language instructions. Even if several operators execute the same instructions at the same time, the problem of accessing a shared resource is solved "inside" the instructions. The solution and implementation are based on linking the high-level language with the factory topography in 3D and adopting the notation of describing this topography, building a mechanism for synchronizing and coordinating access to shared resources, taking into account lean (evaluation of instructions) [20,21]. The aforementioned cycle switching, is carried out by the worker himself, by using the decision tree mechanism. Then this logic is assigned to a given worker or the switching of cycles between workers is carried out by an external object (control unit), which represents, for example, a foreman/manager or an industrial automation system.

The new method based on a high-level script uses the lean management concept and consists of the following steps:

1. Prepare product related data (Bill of Materials).
2. Prepare PFEP (Plan for Every Part) - a database that ties together the parts and the containers in which the parts are transported in the remanufacturing system. When creating the PFEP, complete the container database (dimensions, weight, shapes) and the parts database (dimensions, weight, shapes)
3. Define a group of workstations where disassembly, inspection, reprocessing, re-assembly, and other operations are carried out. Link them to the PFEP.
4. Define workstations within each group
5. Define locations for: containers, operators, machines, material handling equipment
6. Arrange them on the layout
7. Assign a selected/specific part to a specific location
8. Think with work cycles - identify/design work cycles
9. Write down the work cycles with a high-level language
10. Define observation who handles them and when

11. Define Lean value-added attributes (VA, NVA, NVAA) to work instructions. Decide how to present results
12. Define other metrics if necessary - KPIs, WIPs, throughputs.

The methodology outlined above captures 1:1 the workings of the real system.

4. Application in PaaS with Remanufacturing

In this section the application of the proposed approach is provided for remanufacturing process associated with HVC (Hand Vacuum Cleaner). Figure 2 shows the PFEP (Plan for Every Part) built for this product in PaaS.

	Part	Part Name	ID	Length	Width	Height	Capacity	ToteKanban
Row 1	BO1	Housing	KLT6147	0.50	0.20	0.20	5	1
Row 2	BO2	Ball bearing	KLT3147	0.03	0.01	0.05	10	2
Row 3	BO3	Rotor	KLT3147	0.07	0.01	0.05	24	4
Row 4	BO4	Screw	KLT3147	0.01	0.01	0.05	25	5
Row 5	BO5	Sensor	KLT3147	0.04	0.01	0.05	10	2
Row 6	BO6	Spring washer	KLT3147	0.07	0.01	0.05	10	2
Row 7	BO7	Electric cable	KLT4147	0.10	0.01	0.05	8	2
Row 8	BO8	Glue	KLT3147	0.01	0.01	0.05	30	5
Row 9	BO9	Nameplate	KLT3147	0.01	0.01	0.05	20	4
Row 10	S1	Old engine	KLT6147	0.50	0.20	0.20	5	1
Row 11	S2	New engine	KLT6147	0.50	0.20	0.20	5	1

Figure 2. PFEP – Plan for Every Part built for HVC (Hand Vacuum Cleaner) – source: own

The PFEP base was built based on the BOM (Bill of Materials). This is how step 1 and 2 of the methodology was implemented. Figure 3 refers to the Step 3 of the methodology and presents is an inventory of workstations (named Engine_Remanufacturing), which form a group named Line_HVC connected to PFEP named PFEP_HVC.

WorkStation_Name	Line_ID	PFEP_Name	NrLocation	T	NrOperators	N	A	N	N	NrAsstables	NrDisasstable	N	N	NrG_xx	X
Engine_Remanufacturing	Line_HVC	PFEP_HVC	6	L	1	)	)	)	)	1	1	)	)	3	

Figure 3. List of Workstations forming a group Line_HVC connected to PFEP named PFEP_HVC – source: own

Following the Step 5, the locations are defined in the simulation model. A layout of workstation (so-called microlayout), includes machines, buffers/storage fields, and position markers on the floor for operators. The exemplary workstation (from Figure 4) consists of 6 locations: one disassembly table (column NrDisasstables), one assembly table (column NrAsstables), three floor markers (column NrG_xx) and 1 operator (column NrOperators). The workstation is arranged on a layout - Figure 4.

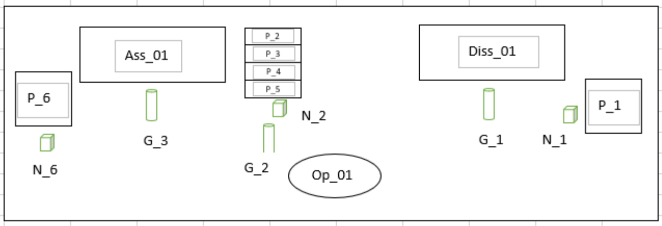

Figure 4. Layout of modeled remanufacturing system – source: own

The markers P_x indicate locations, Ass_01 is the assembly table, Diss_01 is the disassembly table, G_x indicates markers on the floor that form the passage route for the operator, which is marked by Op_01.

A reference process library is created based on standardized work descriptions (work procedures), which determine: 1) who performs certain actions, 2) how, and 3) in what order. The related tables include the example of reference processes written in the described high-level language. These tables are created with the participation of industrial partners in order to develop a library of processes which are relevant for the remanufacturing in PaaS settings (Figure 5). The main goal is to standardize activities so that they are repeatable, measurable, and effective. Thus, the construction of a library of reference

Nr	Work	High Level Script Language
1	Take the engine	N_1 Travel 0 P_1 CheckPartInToteWait1 P_1 LoadFromTote1
2	Go to the disassembly table	G_1 TravelLoaded 0 Diss_01 Unload 1
3	Engine disassembly	Diss_01 Disassembly 210
4	Transport 5 parts from the assembly table to the assembly table	Diss_01 Load 5 G_2 TravelLoaded 0 G_3 TravelLoaded 0 Ass_01 Unload 5
5	Take 4 parts from locations P_02, P_03, P_04 & P_05	G_2 TravelLoaded 0 N_5 TravelLoaded 0 P_2 CheckPartInToteWait 1 P_2 LoadFromTote 1 P_3 CheckPartInToteWait 1 P_3 LoadFromTote 1 P_4 CheckPartInToteWait 1 P_4 LoadFromTote 1 P_5 CheckPartInToteWait 1 P_5 LoadFromTote 1 G_2 TravelLoaded 0 G_3 TravelLoaded 0
6	Place 4 parts on the assembly table	Ass_01 Unload 4
	Installation of a new engine	Ass_01 Assembly 365
7	Check the assembled engine	Work 30
8	Transport the assembled engine	Ass_01 CheckPartOnTableWait 1 Ass_01 Load 1 N_6 TravelLoaded 0 P_6 UnloadToTote 1 G_2 Travel 0
9	Come back	3 Call 1

processes refers to work instructions carried out at a specific the notation described in the previous work [20-21].

Figure 5. The work performed by operator and the corresponding instructions of high level script language – source: own.

Figure 5 shows the cycle work performed by the operator (Work column) and the corresponding high-level scripting language instructions (Step 7-9 of the methodology).

Figure 6A shows a view of the simulation model before the start of the simulation experiment, and Figure 6B after.

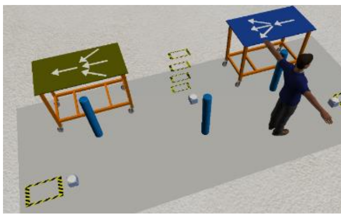

Figure 6A. View of the simulation model before the start of the simulation

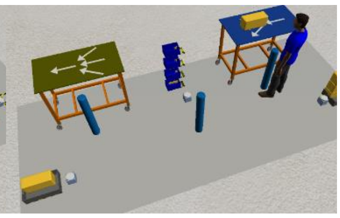

Figure 6B. View of the simulation model after the start of the simulation experiment

The final steps of the methodology include the Lean analysis. Thanks to the high-level scripting language used, corresponding to the work language, it is possible to assign value-added attributes to work routines. These are the following attributes:

- VA – Value Added,
- NVA – Non Value Added,
- NVAA – Non Value Added Attackable,
- Other.

In the simulation approach we apply the well-established in the business practice, tools for Lean analyses which are actionable for decision making for remanufacturing in PaaS, such as:

- Gantt diagrams
- Analyses of VA
- Operator load diagrams – so-called Yamazumi Charts.

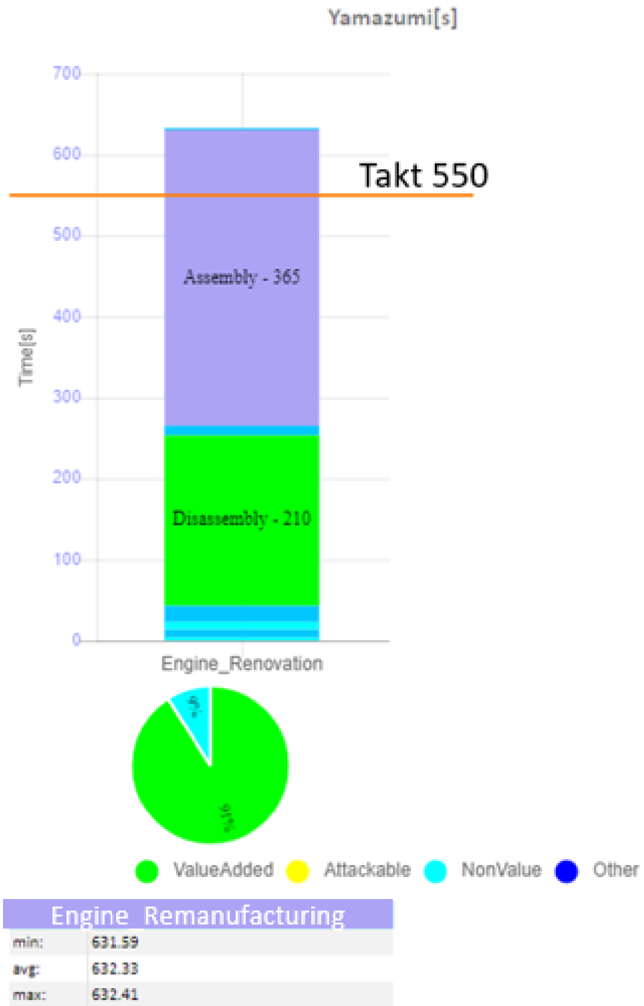

Figure 7. Analyses of value-adding operations (VA), and an operator load diagrams - so-called Yamazumi Charts

5. Conclusions and further works

The application of servitized business models, like PaaS, requires the implementation of value retention processes (VRP). In this paper we focus on remanufacturing as the most resource-efficient VRP. We present a generic PaaS with remanufacturing (Fig.1) and discuss the requirements for simulation approach which includes lean management principles (e.g., reduction of waiting time, reduction of unnecessary transportation).

In this paper, we aim to present a new approach to simulation modelling using a high-level script language, similar to those used by industry experts, according to lean remanufacturing principles. The proposed approach is user-centric, thus facilitates decision making on remanufacturing in PaaS without need to obtain excessive modelling and/or programming skills.

The developed approach allows for the testing of different variants of layout and resources and material flows according to lean remanufacturing principles (to reduce non-value adding activities).

Future research will focus on the extension of the process library in cooperation with industrial partners, in order to better reflect the real-life operations that appear in the remanufacturing process in PaaS. Furthermore, the research will include the development of the hybrid model that incorporates the interaction of remanufacturing with recycling.

Acknowledgements

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