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Simulation Method for Remanufacturing with Recycling – Testing and Project Dimensioning

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Abstract
The article addresses the challenges associated with the Product-as-a-Service (PaaS) concept in the context of the circular economy. The use of simulation technologies within this concept can accelerate the adoption of circular economy principles in companies. It enables faster modelling and optimisation of value-retention processes such as remanufacturing and refurbishment. The aim of the paper is to propose a simulation approach that allows engineers to develop simulation models (digital twins) in the same way they design and redesign closed-loop manufacturing systems. A further objective is to highlight the specific requirements for testing such simulation models and for sizing planned digital-twin projects. The article presents the development of a hybrid model that combines discrete piece-flow for remanufacturing with mass flow (in kilograms) for recycling, using household appliances as an example and identifying sources of uncertainty that affect the organisation of PaaS processes, particularly remanufacturing and recycling. The main contribution is the development of a hybrid simulation approach based on operations in the PaaS domain, i.e. closed-loop manufacturing with the 6R framework, and the application of the COSMIC methodology to size simulation projects. The article also discusses methods for simulation modelling of individual sources of uncertainty and uses an operation-based simulation method instead of conventional discrete-event simulation.

Keywords
Product-as-a-Service, Remanufacturing, Recycling, Simulation, Hybrid model.

Introduction

Several articles have been devoted to this topic, the most important written by Pawlewski (Pawlewski, 2024), where the requirements and challenges for operation-based simulation modelling have been specified. Circular economy, including the concept of PaaS (Product-as-a-Service), poses new challenges to the organization of manufacturing and the feedback loop according to the circular strategies; reduce, reuse, remanufacture, refurbish, repair, and recycle (6R) (Sakao & Nordholm, 2023). These requirements, in turn, challenge simulation methods, which are one of the key technologies associated with Industry 4.0. This is important both in terms of creating new simulation methods and in using them to create digital twins. In essence, for PaaS, digital twins transform the product from a static asset into a dynamic, intelligent system that can be continuously monitored, optimized, and adapted to deliver maximum value to the customer while supporting sustainable practices.

This paper outlines a simulation method that helps engineers build digital twin simulation models using the same process they employ for designing and redesigning closed-loop manufacturing systems. It also highlights the unique challenges of testing these models and properly scaling projects to create digital twins of PaaS systems.

The article pays special attention to the identification of uncertainties characteristic of closed-loop PaaS processes.

This article primarily focuses on:

- The creation of a hybrid simulation model that uniquely accounts for both discrete material flow (measured in pieces, as in remanufacturing) and continuous mass flow (measured in kilograms, as in recycling).
- Pinpointing the uncertainty factors that significantly influence the evaluation of different organizational strategies for PaaS processes, particularly those involving remanufacturing and recycling.

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- The innovative use of operation-based simulation methods as opposed to conventional discrete event simulation.
- A novel methodology for testing various PaaS process scenarios, where testing is not just about error detection but also about exploring diverse process organizations and analyzing how uncertainties impact statistical outcomes.

The paper is made up of 8 sections. The definitions of circular economy processes (including PaaS) and simulation modelling tools and methods are the subject of Section 2. A research gap is described in Section 3 and divided into some detailed research problems: building hybrid model of PaaS, simulation modelling of uncertainty, scenario testing and project dimensioning. The theoretical description of the proposed solutions is presented in Section 4. A presentation of a practical example (implementation) of the use of the proposed solutions can be found in Section 5. The definition of the concept of PaaS scenario testing and the requirements related to this activity are the subject of Section 6. PaaS simulation projects related to the hybrid flow of materials, therefore the problem of their dimensioning, i.e. determining the scale, size, and labour intensity, is crucial for enterprises. These issues aTITLEre covered in Section 7. The key conclusions and future directions are presented in the final section (Section 8).

Methodology

For the research related to the creation of simulation models for remanufacturing with consideration of recycling, a new methodology for creating simulation models was chosen, taking into account the achievements of Lean Manufacturing. The traditional approach to simulation modeling focuses on defining the goal and finding an appropriate solution. This is how the methodologies using simulation are built, proposed both in the literature on the subject (Langley et al., 2009) and in publications offered by simulation software manufacturers (Law, 2007; Borshchev, 2013).

The steps of this methodology are consistent with the Deming cycle – PDCA – a method of operation that allows us to continuously improve, continuously catch errors or waste in work and find solutions to problems (Langley et al., 2009). The Deming cycle consists of 4 stages: Plan – Do – Investigate – Apply. Activities are carried out in a cycle, which means that the cycle repeats itself until satisfactory results are obtained. The methodology defined in this way is universal, general – without taking into account the specificity of the task or problem being solved. And most importantly, the basis of the traditional approach to simulation modeling is DES. The literature shows that the traditional, classical approach to discrete event simulation is an object-oriented approach (Van Mierlo & Vangheluwe, 2018). In fact, describing complex systems using threads and semaphores quickly results in unreadable, incomprehensible, and unverified program code (Lee, 2006). This is partly due to the cognitive gap between the abstractions offered by languages and the complexity of the specification, and sometimes the poorly defined semantics of programming languages, which makes it difficult to understand. An alternative approach is the Statechart formalism introduced by (Harel, 1987). Many simulation programs use state diagrams as the main tool for modeling simulations (Anylogic, Simio). Another modeling tool is Process Flow, offered by FlexSim (FlexSim, an Autodesk Company), which combines a programming language with graphics – replacing computer code with a flowchart in many cases. These tools focus on the details of the modeled system and require the user (production engineer, logistics) to have programming skills and knowledge of a large number (hundreds) of functions. A new methodology that takes into account Lean is OBS (Operation Based Simulation) (Pawlewski, 2024). In the OBS approach, the goal is to bring simulation tools closer to the user, i.e. to create a simulation environment that allows the use of the language of work. This requires adding a new level (hence vertical development) – moving from events to operations – both in the description of the model and in its analysis – moving from the analysis of states to the analysis of operations. This in turn requires the use of a multimodal approach in the description of processes, and consequently a change in the concept of a token. The consequence of this is the definition of a high-level scripting language describing work. This language can only work in a simulation environment that takes into account (contains) the structuring of the factory and the structuring of the process.

Literature review

Closed-loop systems are one of the key elements of the circular economy, which is beginning to replace the linear economy (Genovese et al., 2015; Okorie et al., 2018; Golinska-Dawson et al., 2021). One of the concepts within the circular economy is Product-as-a-Service (PaaS). It is a type of circular business model in which product ownership remains with the manufacturer or PaaS provider, while customers pay a subscription fee or a pay-per-use fee for access to products and/or their functions (Tukker, 2015; Bressanelli et al., 2020). A useful framework to help reduce environmental impact and improve sustainability was defined with '6R': Reduce, Reuse, Remanufacture, Refurbish, Repair, and Recycle (Sakao & Nordholm, 2021). The circular economy prioritises value retention, aiming to extend the lifespan of resources for as long as possible. This restorative and regenerative model, by design, fosters a new supply chain paradigm: the circular supply chain (Ellen MacArthur Foundation, 2013). These circular supply chain systems (CLSCs) integrate material recovery processes such as remanufacturing, recycling, repair, and reuse (Guide et al., 2003); Holgado & Aminoff, 2019). As Golinska-Dawson et al. (2021) pointed out, remanufacturing has become a cornerstone of this emerging circular economy. The concept of remanufacturing suffers from ambiguity due to the presence of several, sometimes conflicting, definitions in the literature (Amezquita et al., 1995; Ijomah et al., 1999; Sundin, 2004; Sundin, 2019). Remanufacturing is defined as an industrial process that involves a complete overhaul of a product. Products are disassembled to individual parts, meticulously inspected, and then undergo various actions: replacement with entirely new parts, reprocessing of usable parts to meet original specifications, and restoration of worn components (Lund, 1985; Lund, 1996). Through this in-depth process, remanufactured products achieve quality standards that are equivalent to or even exceed, those of new product (Lund, 1985). However, remanufacturing typically requires more effort and resources compared to refurbishment.

Recycling is the process that breaks down used products into their base materials through various separation techniques. These recovered materials can then be used to create entirely new products. Recycling usually results in a loss of the original product's form and functionality of the original product.

Fig. 1 shows the flow of materials in a PaaS loop, where the '6R' icon identifies the decision on what to do with the delivered product – in the case analysed, this refers to the decision to direct the used product to remanufacture or recycle.

Simulation modelling of a remanufacturing process is challenging, as a remanufacturing process can differ between products. The most generic stages of the processes are: core collection / delivery (used product), inspection, disassembly, cleaning, sorting, reprocessing, dispatching, reassembly, and final testing (Golinska-Dawson, 2019). Studies on simulation in remanufacturing are limited. Most existing studies apply the discrete event simulation (DES) approach to cope with remanufacturing uncertainties (Golinska-Dawson & Pawlewski, 2015; Golinska-Dawson & Pawlewski, 2018). More complex approaches are rare. An example of a more holistic approach is the work of Goodall et al. (2019), as they have proposed a data-driven approach that includes three elements: 1) an adaptive remanufacturing simulation algorithm for modelling of material flow in remanufacturing; 2) an information model; 3) a service layer to collect and analyse sensor data. A good overview of the literature in this area can be found in (Okorie et al., 2024). (Weidmann et al. (2015) have also identified Agent-Based Simulation (ABS), System Dynamics (SD) and DES, as appropriate methods for the simulation of product as a service approach. They applied DES to forecast and evaluate different scenarios, but did not consider value retention processes.

DES – Discrete Event Simulation – is a modelling technique in which any changes in the simulation model are represented by events (nodes) that occur at the time when certain conditions occur. Such models are typically represented by event graphs with nodes and dependencies between them (arrows). Each event occurs at a specific point in time and represents a change in state in the system. It is assumed that there will be no change in the system between events. In this way, the simulation time can jump directly to the time of the next event (Siebers et al., 2010).

ABS – Agent-Based Simulation – is a powerful simulation technique that models complex systems using autonomous components called agents (Golińska & Hajdul, 2011). These agents interact with each other and their environment, influencing the overall behaviour of the system. The behaviour determines its role, how it interacts with others, how it responds to messages, and even if it can adapt its behaviour based on the environment (Mustafee & Bschoff, 2011).

In conclusion, 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 that help a company in remanufacturing in PaaS are lacking. Therefore, effective attempts are being made to change the approach.

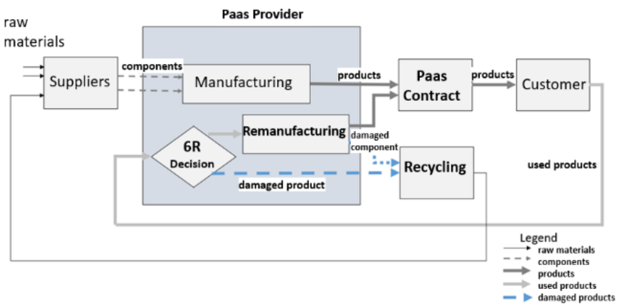


Fig. 1. Material flow in the PaaS loop studied in the research.

On the one hand, using the concept of a digital twin, i.e. a virtual representation of a physical system, i.e., an environment, process, object with its elements, features, and functionalities, the level of reflection of which enables the simulation and evaluation of alternative scenarios of the future without any loss of quality of simulated events compared to real events in terms of the key parameters for the decision maker (Kosacka-Olejnik et al., 2021). On the other hand, the authors are working on changing the approach to simulation and proposing an approach defined as OBS – Operations Based Simulation (Pawlewski, 2024). This novel approach is based primarily on defining a high-level language that allows describing work instructions used in industrial reality in a simulation programme. The feature of this language is the representation of work performed in reality in the form of work cycles in exactly the same way - 1:1. In this way we define adequacy, the full compliance of the model with reality. This is very difficult to obtain using other simulation methodologies, especially those based on DES. They should take into account those features that the employee naturally uses, i.e. his orientation in space, operation in the check and wait mode, i.e. first check whether the conditions for the task are met, if not, wait until they are met. This mechanism should also include solving the problem of access to shared resources, e.g. when two or more employees try to access a common resource, e.g. by taking a part, tool, or container. Fulfilling these requirements will allow assigning to instructions attributes of work that adds value (VA – Value Added), work that does not add value (NVA – Non-Value Added), but which must be performed, e.g. quality control, and work that does not add value but is susceptible to attacks, i.e. we want to minimise and eliminate it (NVAA – Non-Value Added Attackable). Embedding such a defined language in the simulation programme allows for the construction of operator work cycles identical to those in reality (1:1) and automatic performance of VA analyses (Value-Added Analysis) and automatic generation of operator load diagrams, the so-called Yamazumi diagrams. Incorporating other Lean tools into the simulation programme, such as PFEP, Andon, and Kanban, required the development of a factory structuring and process structuring concept.

Problem Definition

In the context of PaaS, a hybrid model is understood as a model that combines the flow by pieces (typical for remanufacturing) with the mass flow by kilogrames (typical for recycling). Such a situation is shown in Fig. 2, which is an extended section of Fig. 1.

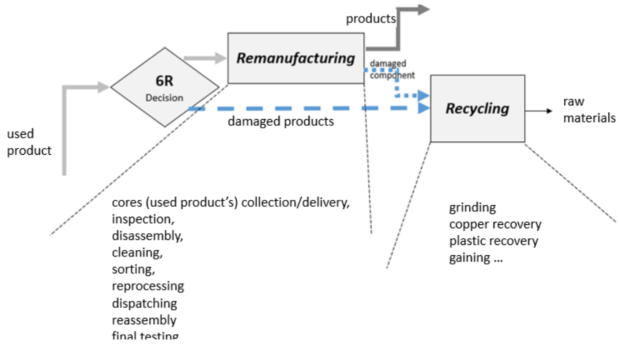


Fig. 2. Operations carried out in the remanufacturing and recycling phase of a PaaS loop within this research.

Remanufacturing, refers to the flow of pieces, while recycling refers to the flow of mass measured in units of mass. Mass is a quantity that characterizes substances, it is used to quantify their inertia – it is a measure of the amount of matter. The basic SI unit of mass measurement is the kilogram [kg]. The mass flow is the result of using the grinding to recover individual material fractions. Grinding is a destructive operation. Its effect is to enable the separation of individual material fractions enabling the recovery of raw materials on an industrial scale.

On the one hand, the research problem is also the choice of simulation technology and modelling approach using the digital twin concept, on the other hand, the research problem is also the identification and modelling of the uncertainties that are associated with this process. Unlike traditional manufacturing, where there are almost no uncertainties related to the quality of parts and components, these uncertainties are a characteristic feature of remanufacturing, because it is not known in what condition individual components are worn.

In this context, there is also the challenge of testing scenarios – but in this case, the purpose of testing is not the traditional search for errors and malfunctions, but testing various scenarios related to the organization of the remanufacturing process in order to find a good solution.

The last research problem is the dimensioning of hybrid PaaS simulation model. The implementation of a PaaS digital twin project in the field of remanufacturing and recycling is a large IT project. The scale of the project depends on the size and scale of the PaaS Provider. A digital twin is a software model dedicated to a specific Provider. It is a significant element of the budgets of organizations implementing Industry 4.0 projects, which is why these organizations see the need to control the expenses incurred and analyse the effectiveness of the implementation of funds allocated for the maintenance and development of digital twins. It is therefore necessary to have measures that allow you to analyse both the quality and productivity of the inputs associated with their development and maintenance.

Solution Proposal – Theoretical Description

As stated in Section 3, the essence of the problem is the uncertainties that are a feature of hybrid PaaS processes. Solving the research problem related to modelling these uncertainties will be the basis for building a hybrid model for the PaaS system, which is the main research task (problem).

Referring to Fig. 2, two groups of uncertainty are defined:

- Global (icon "6R" in Fig. 2) related to the uncertainty of supply (N1) – this results in the use of a given piece of washing machine immediately for recycling or remanufacturing.
- Local, which is related to the remanufacturing process (icon "Remanufacturing" in Fig. 2) and refers to the quality of component parts (N2) and the duration of the operation (N3) and related to the recycling process (icon "Recycling" in Fig. 2) and refers to uncertainty in material fractions (N4).

It is proposed to model these uncertainties at the high-level language, so called the language of work routines, that describes the activities of operators (Pawlewski, 2019). Modelling at the high script level consists of operations that are related to defined uncertainties.

N1, N2 – supply and quality uncertainties are proposed to be modelled with a decision instruction that changes the work cycle performed by the operator. It is proposed to add a statement to the high-level language called CheckStochastic, whose parameter is a number specifying a percentage. This instruction transfers control to cycle A if a number below a specified threshold is drawn, and to cycle B if a number above this threshold is drawn. The number is selected randomly at runtime, for example according to a statistically uniform distribution. Figure 3 illustrates such a jump.

N3 – the uncertainties related to the duration of operations are proposed to be modeled by the variable time of these operations defined by statistical distributions assigned to a given work. Work operation has parameter – this is a pointer to a list of statistical distributions – Fig. 4. In this figure Uniform means normal distribution and Loglogistics means log logistics distribution.

N4 – uncertainties related to the material fraction are proposed to be modelled with a special instruction, which results in a random change in the mass of material streams and separation of these streams.

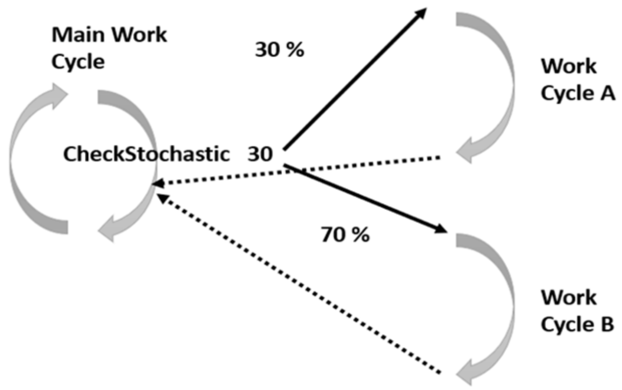


Fig. 3. Presentation of cycle change related to supply uncertainty (N1) and component quality.

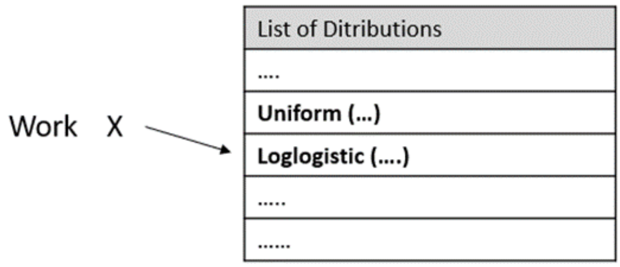


Fig. 4. Presentation of the relationship between the Work operation and the list of statistical distributions assigned to a given work.

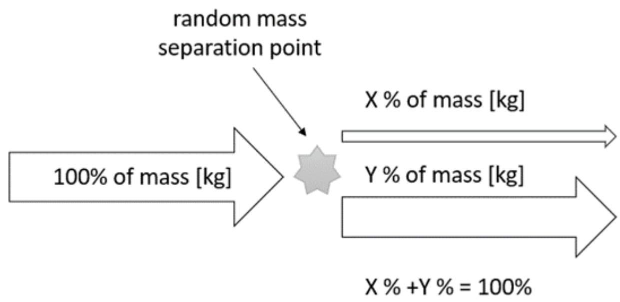


Fig. 5. Model of mass streams with random mass change.

Solution Implementation

The LogABS application was used to implement the proposed solutions. It is an application built according to the guidelines in article (Pawlewski, 2024) based on operations and on a multimodal approach. It is an extension of DES simulation that uses a high-level language to describe the work. The application includes built-in Lean mechanisms – value-added analysis, andons, kanban, yamazumi, etc. As part of the project, the results of which are discussed in this article, the LogABS application has been extended in such a way that it is possible to implement the solutions presented in Section 4 of this article.

For uncertainties N1 and N2, the CheckStochastic statement with parameter X has been introduced into the high-level language instruction set. Parameter X specifies, either in percentage terms or via a stochastic distribution, the proportion of cases in which the next operation will be executed and the proportion of cases in which the subsequent operation in the work-cycle array will be performed. This makes it possible to define an alternative duty-cycle call for a specified percentage of cases.

For uncertainty N3, the existing Work instruction has been extended with an additional parameter, which is a pointer to an array containing the names of the given operations and the corresponding statistical distributions with their parameters. There can be many such arrays, they are assigned to a given station in the simulation model. That is, they should contain a description of the operation (work performed) in a given position. This parameter includes an address of the array (with the name of the position) and a row number. In the table, there is a description of the statistical distribution along with its parameters. This situation is shown in Figure 6.

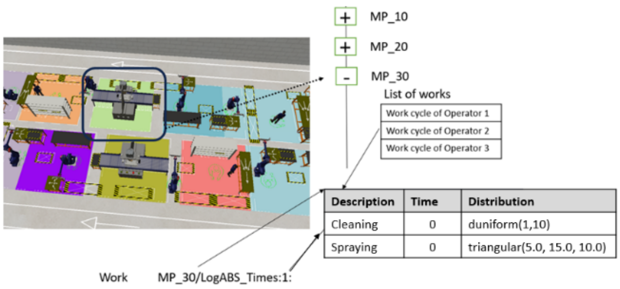


Fig. 6. Implementation of Work instruction in application LogABS.

Testing – Definition of Requirements

The concept of testing has a broad meaning depending on the area of research in which it is used. Traditionally, testing refers to looking for errors and checking if something (machine, software, etc.) works as intended. With regard to software, it is a process consisting of all the activities of a life cycle, both static and dynamic. Focused on planning, preparing, and evaluating software and related products, it can be determined whether they meet the specified requirements, demonstrate that they are fit for purpose, and detect defects. However, in the context of PaaS, it is proposed to extend the meaning of this concept to include testing various scenarios related to the organisation of the remanufacturing process.

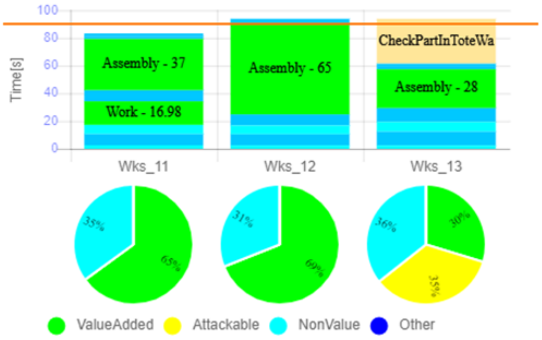
In the hybrid model, there is a piece flow for the remanufacturing process and a mass flow (in kilograms) after the grinding operation in the recycling process. The mass flow is, by its nature, a push process due to the characteristics of the operation and the use of conveyor belts. The main grinding operation tends to “clog” the system, creating potential bottlenecks.

The remanufacturing process is characterised by a large amount of uncertainty both regarding the quality of parts/subassemblies – N2 and the operating time – N3. This makes the organisation of the remanufacturing process difficult and is the key to its effectiveness. The amount of uncertainty makes the process dynamic, and the simulation method, i.e. testing various scenarios using time compression, is appropriate in this case. Assuming a large number of processed products, it is logical to organise this process in-line, using the Lean achievement. The remanufacturing process can be organised inline, in push logic or in pull logic.

Individual workstations carry out their operations in a specific time – a cycle that is likely to change. In this case, it is difficult to talk about the calculated tact, because we do not have exact times of the operations. Therefore, it is proposed to use Yamazumi diagrams in simulation modelling and introduce them into the methodology of simulation modelling of PaaS processes. The result of the testing will be sets of Yamazumi diagrams, which will be the basis for further conclusions and will determine the organization of this process. The diagram was prepared in such a way that in one drawing (Fig. 7) you can see a bar (stack) chart of the performed operations, a cookie chart showing the analysis of the added value and a table with the values of the minimum, average and maximum cycle lengths. The Yamazumi diagram is implemented for the desired number of cycles, giving the initial measurement time in the simulation experiment.

Design Dimensioning

A digital twin factory (DTF) is a software model dedicated to a specific factory. It is a significant element of the budgets of organisations implementing Industry 4.0 projects, which is why these organizations see the need to control incurred expenses and analyse the effectiveness of the implementation of funds allocated for the maintenance and development of DTF. Therefore, it is necessary to have measures that allow the analysis



	Wks_11	Wks_12	Wks_13
min:	76.86	93.80	93.78
avg:	83.25	93.80	93.80
max:	87.48	93.80	93.80

Fig. 7. Yamazumi diagram in LogABS application containing bar chart, pie chart and table of minimal, maximal and average value of work cycle time.

of both the quality and productivity of expenditures related to the development and maintenance of DTF.

Software dimensioning is mainly used to estimate the scale of implemented IT projects. Unlike other methods, it is an objective measure that focusses on user requirements, not workload or costs of work. A major advantage of this method is that it can be calculated by both the ordering party and the contractor, and even before work begins, solely on the basis of requirements. In this approach, the unit of software size is function points, which for both parties constitute the basis for estimating, among other things, the time needed for its production and the budget necessary for project implementation. This is a standard recognised worldwide, which can be used for almost every project. The greatest advantage of this method is that it is independent of specialists, contractor, margin or technology in which the software was created. Therefore, function points are practically a universal currency for measuring software, which can be the basis for settling the contractor's accounts (i.e. payment of remuneration), but it is also perfect for comparing the efficiency of different contractors within the same or different projects.

The creation and maintenance of DTF is valued based on the number of Function Points designated for the created and modified DTF. The COSMIC method in version 3.0.1 with extensions described in the document (Abram et al., 2009) was adopted as the basis for determining the number of Function Points. This method was adapted to the needs of DTF by the main author of this paper under the name Cosmic-DTF.

The COSMIC-DTF method consists in applying a series of actions defined by the rules and principles of the COSMIC-DTF method to the functional user requirements (FUR). The effect of these actions is to obtain a value representing the functional size of the selected DTF element, defined in COSMIC Function Point units. The basic assumption of the method is that the functional size of the DTF is directly proportional to the number of OBS elements within a given DTF. Thus, the canonical form of the method assumes that for specific functional requirements, functional processes (Functional Process) and data groups (Data Group) should be defined. Functional processes are the result of actions related to the structuring of factory processes, while data groups are the result of actions related to the structuring of factory. Functional processes represent a unique, independently executable sequence of actions (route) in order to implement manufacturing processes in DTF. Data groups describe the factory resources that enable the implementation of manufacturing processes and constitute the mechanism for implementing functional processes (routes).

When identifying data groups, they are assigned to one of thirty-three categories. Data Groups, Position, PDKC, Parts, Containers, Equipment, Tractors, Logistic wagons, Employees (in database), Robots (in database), Manipulators (in database), Forklifts (in database), AGVs/AMRs (in database), Machines (in database), Conveyors (in database), Drones (in database), Local markers (at the workstation), Global tags, Logistic train stops, Trains, Sectors, Locations (at the workstation), Andons (at the workstation), Tunnels (at the workstation), Work tables (at the workstation), Assembly tables (at the workstation), Automatic assembly (welding) machines (at the workstation), Disassembly tables (at the workstation), Attributes, Operators (at the workstation), Universal Operators (Workstation), Conveyors (at the workstation), Shapes (at the workstation). When identifying functional processes, they are assigned to one of 7 categories:

1. Cycle (route)
2. Logical table
3. Decision Tree (CycleFlow) – cycle execution logic
4. Logistics Navigator
5. Logistic Train Mission
6. Logistic train schedule
7. Production plan

It is also necessary to take into account the specifics of the factory, the industry, which may define special requirements, which are assigned to one of 4 categories:

1. Report – KPIs
2. Special Function
3. Special data group
4. Lean special instruction (or modification)

The presented methodology was used by the author in the project of building a digital twin for an FMCG (Fast-Moving Consumer Goods) company (The digital Twin of Factory, 2024). It is being adapted to the requirements of remanufacturing with recycling and in this article it is described for the first time.

Conclusions and Further Work

The article presents the results of the ongoing project of developing the concept of simulation modelling for the SCANDERE project – Scaling up a circular economy business model by a new design, leaner remanufacturing, and automated material recycling technologies (scandere.nu, 2024).

The main contribution of the authors is the development of the approach to simulation based on operations in the area of PaaS, i.e. closed-loop remanufacturing and recycling, and the use of the cosmic methodology for dimensioning simulation projects.

The article presents the key solutions for modelling the uncertainties that are characteristic of these processes and also presents the essence of the hybrid model combining the flow by piece (characteristic of remanufacturing) and the mass flow (characteristic of recycling). These uncertainties were defined and methods for their modelling were proposed. The proposed solutions are embedded in a newly defined operation-based simulation environment that enables the implementation of lean principles, which in turn results in the possibility of implementing leaner remanufacturing. The proposed approach based on operations also provides great opportunities related to scaling models. Considering the complexity of industrial Paas systems, the ability to scale operations, i.e. their arbitrary decomposition and synthesis depending on the need, provides a huge advantage over other solutions. It also defined the requirements for testing flow organization scenarios in remanufacturing systems and the principles of creating digital projects using simulation for PaaS processes. This, in turn, sets the direction for further work, such as:

- Creating scenarios for the organization of remanufacturing and recycling systems for various products that are described by statistical distributions, the result should be the rules for creating reference models.
- Checking the effectiveness and implementation of the proposed principles for dimensioning PaaS simulation projects.

Acknowledgments

The article focusses primarily on PaaS related to household appliances – it presents the effects of the project SCANDERE 'Scaling up a circular economy business model by new design, less remanufacturing, and auto-mated material recycling technologies' granted from the ERA-MIN3 program under grant number 101003575. Poznan University of Technology was financially supported by NCBR, National Centre for Research and Development, Poland (No. ERA-MIN3/1/SCANDERE/4/2022).

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