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Proposed framework for flexible de- and remanufacturing systems using cyber-physical systems, additive manufacturing, and digital twins.

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Abstract

Under the circular economy paradigm, de- and remanufacturing systems are more relevant than ever. However, such systems present specific challenges related to the system structure, automation, and recovery of complex products. At present, operations such as disassembly and quality assessment of returned products largely depend on manual labor and the high variety of returned products makes restoring disassembled parts demanding. This paper proposes a framework for de- and remanufacturing systems based on Human-Cyber-Physical Systems (HCPS) that includes additive manufacturing for refurbishing damaged parts during the remanufacturing process. The framework is illustrated using MANULAB at NTNU.

Keywords: additive manufacturing, reconditioning, circular manufacturing, digital twin, cyber-physical-systems, circular factory

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1. Introduction

The main idea behind circular manufacturing (CM) is to provide functionality for users with lower resource consumption and environmental load and it is framed by the principle of reuse [1]. The purpose of reuse is then understood as “to exhaust the lifetime of products or parts through multiple users or multiple products, respectively, to reduce the number of products or parts needed to satisfy the requirements of a certain group of users for a certain period of time” [2]. The extant literature refers to reuse as different processes such as: remanufacturing, reconditioning, multi-cascade reuse, and it can also refer to products and parts [1, 3, 4].

Reconditioning is the process of restoring the quality of a component to a certain level with medium level of work. AM is a technology with great potential for flexible reconditioning. However, in the circular factory where both manufacturing and reconditioning operations are performed, integrating AM for reconditioning is challenging. The system design and decision-making processes need to be synchronized, interconnected, and flexible.

Nomenclature

AM	Additive Manufacturing
CM	Circular Manufacturing
CPS	Cyber-Physical Systems
DT	Digital Twin
EoL	End of Life
FFF	Fused Filament Fabrication
MES	Manufacturing Execution System
PCB	Printed Circuit Board
PLC	Programmable Logic Controller

Cyber-Physical Systems (CPS) are proposed as enablers of circular manufacturing systems since they can support rapid configuration and improvement [4, 5]. CPS are interconnected cyber and physical systems that are operated, monitored,

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controlled, and coordinated by a computing and communicating core [6]. This paper proposes a framework to integrate AM in reconditioning within the paradigm of the circular factory with a Cyber-Physical System (CPS). A general understanding of the system design is suggested, and the critical decision-making process is discussed. Finally, an illustration case is presented using MANULAB at NTNU for its conceptualization.

2. Additive Manufacturing for reconditioning

The characteristics of AM have aspired great interest in the technology for refurbishing and reconditioning components for circular manufacturing [7]. The layered manufacturing technology enables the restoration of worn surfaces and even (re)protrusions. Consequently, the reconditioning of components using AM inevitably becomes a hybrid manufacturing process involving both additive- and subtractive manufacturing processes.

Because AM relies on a digital model for process planning, the current and final desired geometry must be obtained. While the final geometry may be available in a database, the current state of the component needs to be digitized. This can be achieved in a number of ways [8], of which non-contact methods are preferred for flexible and automated systems. After the current and desired geometries are digitized, the sequence of processes can be planned. The reconstruction of CAD models and process planning for reconditioning remains an active field of research [9-11].

3. A Framework for AM in the CPS Circular Factory

The proposed framework is based on the concept of the circular factory. In which the system should be able to perform both manufacturing and reconditioning operations [4]. In addition, it presents AM as the main technology for reconditioning in CPS architecture. We consider an item as being an assembly of components. The proposed process plan of the circular factory system consists of four material flow stages (figure 1):

i. *The operations to process the items being manufactured*. This stage is the conventional linear manufacturing operations where there is a process flow that takes raw material and produces/assembles components to manufacture a product.
ii. *Usage of the Item*. The item exits the factory and is used. In this stage, the users' requirements are matched with the item's functionality.
iii. *The collection of the items after use and life cycle evaluation*. The collection of the item can either be planned or spontaneous. Once the item is returned to the factory it is disassembled, sorted, and cleaned. An assessment process is performed to decide the life cycle treatment the item is going to have. Following the classification of Sakai and Takata[1], four EoL treatments are considered: (i) reuse which entails low level of work (i.e. cleaning) before return to user, (ii) remanufacturing which requires high level of work and the item can be sold as new, (iii) reconditioning which assures a warranted item but not equivalent to a new product, and (iv) recycling as a last resort if all the other options are exhausted.
iv. *Reconditioning with AM.* The four phases of reconditioning are illustrated in figure 1 based on [12]. Once the component has been reconditioned, it is sent back to the manufacturing process to be reassembled using reused parts that have been repaired from other collected products, or they are replaced by new parts.

The circular factory system with reconditioning produces three types of items: reuse, reconditioned, and new. They all have different quality levels with different workloads but providing the same function.

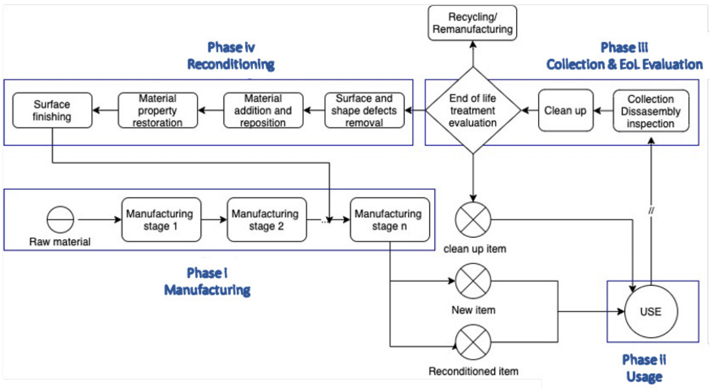

Figure 1. Proposed Circular Factory System Structure with Reconditioning

The proposed system performs the assembly of new and reconditioned items on a continuous flow using the same manufacturing system infrastructure. Such a task is complex since it requires synchronizing information from different sources such as customer orders, raw material buffers, inventories, and planning accordingly. However, in a CPS the operation management of the circular factory is aided by Manufacturing Execution Systems (MES) and Digital Twins (DT) connected to the physical system.

3.1 Workflow of AM for reconditioning

The workflow of the framework considers both material and information flow. Given that is a Cyber-Physical system the material flow is controlled by a MES that is connected to the physical system via sensors and PLCs. The steps of reconditioning in figure 1 are transformed to use AM as technology for reconditioning based on [13]:

- *CAD model regenerated and new.* In this step, the component to be reconditioned is scanned and a CAD model is generated. The CAD of the item in processing is compared with the CAD of a new item. With this information, a manufacturing strategy of subtraction or addition is selected.
- *Material subtraction and addition and deposition*. The component passes through additive and subtractive processes to realize the desired geometry.

- *Material properties restoration.* Depending on the AM technology, infiltration, curing, etc. may be required to restore material properties to a satisfactory level.
- *Surface finishing.* The surface from AM processes is rough and requires additional processing to reach the desired quality level.
- *Inspection*. The component is inspected for quality discrepancies, including surface properties, dimensions, and geometric deviations. If the conditions are not fulfilled, the component is sent back to EoL evaluation for recycling or to reenter the reconditing phase if it is possible to reach the required properties.

3.2 Decision-making process in the Circular Factory System

The material flow of the proposed framework is moderated by several complex decision-making processes. Some of these processes are related to planning and scheduling the assembly of manufactured and reconditioned items interchangeably in the same system layout. Others are related to quality and tolerance assessment of the components. The most critical decision-making stations in the process are:

- *EoL treatment evaluation.* The item has been previously disassembled and cleaned. For the EoL assessment, it is necessary to collect data about the quality of the components and their level of functionality. The data is collected using wireless and visual sensors and harmonized to be processed by a numerical twin. Umeda et. al [14] consider four conditions to successfully reuse a component.
  The first condition is the residual lifetime of the component, which needs to be long enough comparing to the item to be installed. Therefore, the system needs to have a record of the residual lifetime of the component to match it to the item in which it will be installed. Such records can be stored in smart tags or printed sensors in each component which are read by CPS sensors and transferred to the MES.
  The second condition is the cost of reusing the component should be affordable comparing to the cost of making a new one or treating the component as waste. Feed-forward processes should be applied to evaluate the satisfaction of this condition. Knowledge about the cost of reconditioning, remanufacturing, and recycling should be available considering all the possible variations such analysis presents.
  The third condition is the remaining value and quality of the reusable component that should satisfy those required by the destination item. In the proposed framework we proposed two levels of quality according to the EoL treatment based on [1] (low for clean-up and medium for reconditioned) and one functionality which is the same as the new item. The calculation of the remaining value and quality of the component should be performed by a feed-forward system that compares the potential quality of the reused item after treatment with a benchmark previously defined.
  The fourth condition is a balance between the supply and demand of reusables. For this condition, Umeda et. al [14] proposed the marginal reuse rate.
  The first and third conditions are the determinants in choosing the life cycle option. The second and fourth are economic and market constraints to the circularity of the components and items.

  Evaluating the life cycle option for each component is a complex process that requires not only an advanced CPS with feed-forward mechanisms, but also experienced operators. Given the uncertainty in the state of the returned product and the current state of the art, the automated system will need to be aided by humans.

- *Manufacturing strategy in reconditioning.* Comparing the CAD model of the component to be reconditioned to a benchmark CAD model can either be automated using a machine learning algorithm or a hybrid system where humans are aided by digital shadows/twins [15]. In a circular manufacturing setting, the system will only receive components where the original CAD model is available. A 3D scan of the current geometry will produce a point cloud from which the volumetric deviations can be derived. Automated process planning can be achieved for geometries of low complexity and with minor defects. Larger deviations and complex geometries may require human interaction in a hybrid system enabled by the CPS.

- *Quality inspection after AM operations.* The quality of the component can be checked using vision-based systems. This quality assurance can be automated using machine learning algorithms.

- *Planning and scheduling operations.* One of the most challenging parts in planning in an integrated disassembling, reconditioning, and manufacturing system is balancing supply and demand in terms of volume and quality. To solve this problem, several strategies of collection have been proposed [4]. Once the collection strategy is strategy is worked to mitigate volume imbalance, the challenge is shifted towards the scheduling of the different operations in the same process layout. Which operation should be prioritized: assembly of reconditioned items, or manufacturing of new items? Simulations run in digital models connected to the MES are tools to aid the human planer to develop proper heuristics and suggest optimal configurations.

- *Inventory Management of new and reconditioned items.* This decision is highly dependent on the collection strategy and the balance between demand and supply.

- *Collection Strategy.* Planed circulation is proposed as an effective strategy to solve the problem of volume imbalances in supply and demand [16]. In case such strategy is not possible, spontaneous collection will have uncertainties about volume and quality that will affect inventory management and planning and scheduling. Forecasting models, as well as simulations, are proposed as tools to aid the decision-making process [17, 18]

3.3 Critical issues for decision-making in reconditioning process with AM

Fully automated decision-making in the reconditioning process is highly problematic because of the level of uncertainties in the condition of the component. This is especially difficult when the collection strategy is spontaneous. Given that the reused item is to provide the same functionality as new products, they could be outdated [1]. To solve this problem some studies have focused on production planning and sales planning to optimize demand imbalances by modeling uncertainty [19]. However, reconditioning with AM can be used to upgrade the component by addition or subtraction of material [20]. This required that such upgrades are considered in the design of new models and that humans are involved in the decision process of evaluating the life cycle option and reconditioning strategy. Therefore, human-machine cooperation is suggested where data and analysis from feed-forward systems and AI are combined with human heuristics and experience.

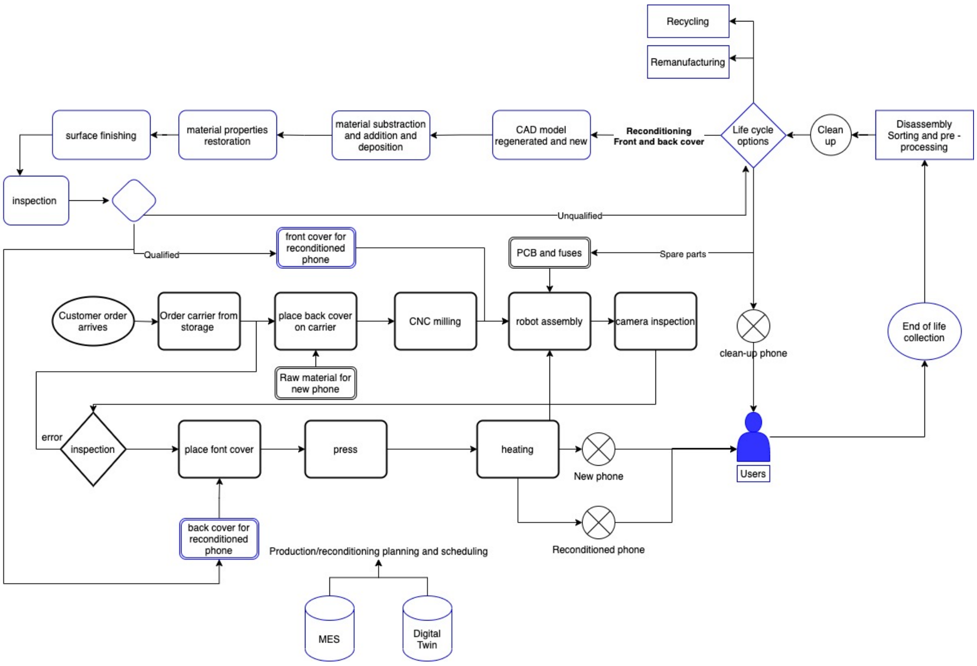

Fig. 2. Illustration of the proposed framework in MANULAB

4. Cyber-Physical (CP) Factory Illustration Case

4.1 CP Factory MANULAB

The illustration case presented in this paper is conceptualized at the CP Factory in MANULAB of the Norwegian University of Science and Technology. The lab is composed of a fully automated assembly line developed by Festo® Didactics which assembles a mobile phone. The phone has the following components: front and back cover, fuses, and a Printed Circuit Board (PCB). And MES software receives information from the assembly line which can also be connected to a digital model of the same system. In the process of creating a new phone, the customer order is sent from the MES and the raw material for the back cover of the phone is placed on the carrier. The milling machine processes the raw material to make it ready for the PCB. Then the carrier is transported to a robot assembly where the PCB and the fuses are placed on the back cover. A camera inspects the components to check if the fuses are placed correctly, in case of error the carrier is sent back for rework. The front cover is placed, pressed, and heated to finish the new product (figure 2).

4.2 AM reconditioning mobile phone cases

In the system design illustrated in figure 2, the phone covers are the components eligible for reconditioning with AM. PCB and fuses are inspected for quality and functionality. Those fulfilling the requirements are sent as reused parts for assembling reconditioned phones, otherwise, they are directed to recycling. The process of reconditioning considers the five stages described in section 3.1. The milling machine will work in coordination with a fused filament fabrication (FFF) 3D printer to recreate the slots and bosses that keep the PCB in place. Similarly, a snap-fit mechanism is maintained between the front and back covers. The inspection of the tolerance dimensions and quality of the cover is done using a visual system. If the cover is not qualified it can either be reworked if possible or send for recycling. The process of reconditioning is also controlled via MES connected to CAD software and a digital model that run simulations to virtually test various geometries.

4.3 Critical issues for implementation of AM in the illustration case as a circular factory

At present, the automated solutions for reverse engineering CAD models may not be adequate to support a fully automated system for refurbishing components in a hybrid additive-subtractive system. However, with low variation in product designs where the CAD model is available, the process planning required to close the gap is manageable. Applying machine learning in a CPS to improve performance over time may reduce – or even eliminate the need for human operators for such tasks in the future. Nevertheless, the human component should be retained to ensure quality and continuous improvement in manufacturing processes.

The MES software needs to keep track of which components are for new phones and which for reconditioned ones. Inventory management also needs to discriminate the volume of the different components for each process (new, reconditioned) to match customers' orders with planning and scheduling. The CP factory of MANULAB gives the possibility of tracking the carriers through the system using smart tags and wireless sensors. Therefore, each component should be stored and transported on a carrier with smart tags. Another possibility is to add printed tags to the components that can be read by the existing sensors.

5. Conclusions

AM technology combined with CPS and DT environments has the potential to support the realization of reconditioning systems synchronized with conventional manufacturing operations. In this paper, we present a framework that illustrates how such a system could look like. The framework is visualized in the CP factory of MANULAB at NTNU.

Acknowledgments

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