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A manufacturing process digital twin network addressing business added value

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Abstract

Digitalization seems to be the main drive towards sustainability in manufacturing, with one aspect of it being the digital twins for manufacturing processes. At the same time, sustainability, through its threefold character, namely addressing people, planet and profit aspects, introduces many different KPIs that need to be taken into account. Thus, adopting such a digitalized workflow, through a single manufacturing process digital twin network addressing sustainability, leads to changing also the workflow of a business, in order to harmonize materials and information exchange. The current work introduces a meta-modelling framework towards achieving heuristic modelling of a workflow and assessing the impact of the digital twins on the business workflows with respect to the complexity and potentially the profit of technology integration.

Keywords: Digital twin, manufacturing process, certification, complexity, workflow

1. Introduction

The recent digitalization trend is promising in terms of achieving various targets [1] and it seems that many benefits arise through it, including sustainability [2]. Additional objectives are the social related aspects, the manufacturing agility [3], as well as the digitalization, a highly adjustable (per case) concept [4-5].

Furthermore, the integration of innovation, in general, is highly relevant, especially in cases where investments are limited, such as the microfactories [6].

Despite the corresponding integration of technologies, it seems that there is need for a framework to handle all this, taking into account business level changes that accompany this transformation. Furthermore, activities involved, like Blockchain-based certification, have costs involved [7] that need to be taken into account. With all these in mind, it seems that business aspects should be embedded together with manufacturing modelling, even if the reference is manufacturing process level. This embedding could be made through graphs theory which has been used before in both business [8] and production modelling [9]. In any case, monetary aspects being raised also from networking capabilities [10] that are facilitated through digitalization are another aspect that should be taken into consideration.

Reporting, especially in the context of certification is highly involved in many cases and can drive strategies such as resources' and energy efficiency [11]. In particular, on-board fuel and/or energy consumption monitoring devices [12] link manufacturing to design and to use phase, creating the so-called "context awareness" [13]. As a matter of fact, it seems that non-financial reporting [14], a more generic term, is a formal directive that drives innovation and "green manufacturing" forward in a certifiable way.

This interconnectivity is a characteristic feature of Industry 4.0 and it seems that Digital Twin networks [15-16] can boost these hyper-complicated workflows. In particular, a Digital Twin for each involved actor can provide and/or retrieve information to/from another. Equivalently, some sort of Edge Intelligence [17] is required for each functionality within lifecycle (Fig. 1). There are various challenges in this, such as: (a) modelling the interaction of digital twins, (b) automating the information exchanges and (c) implement secure certification.

The current work is a first approach towards estimating the impact of integrating digital twins at business level and network-wise. To this end, a meta-modelling framework is introduced, based on graphs and transactions. The framework is given in the next section, followed by some preliminary results and discussion on various aspects of the respective impact.

2. A heuristic and conceptual framework

To achieve the implied cloud and edge intelligence through a corresponding digital twin network, one would require to first define the workflow through an intuitive and rigorous tool. Graphs theory may be the best option for modelling a production workflow.

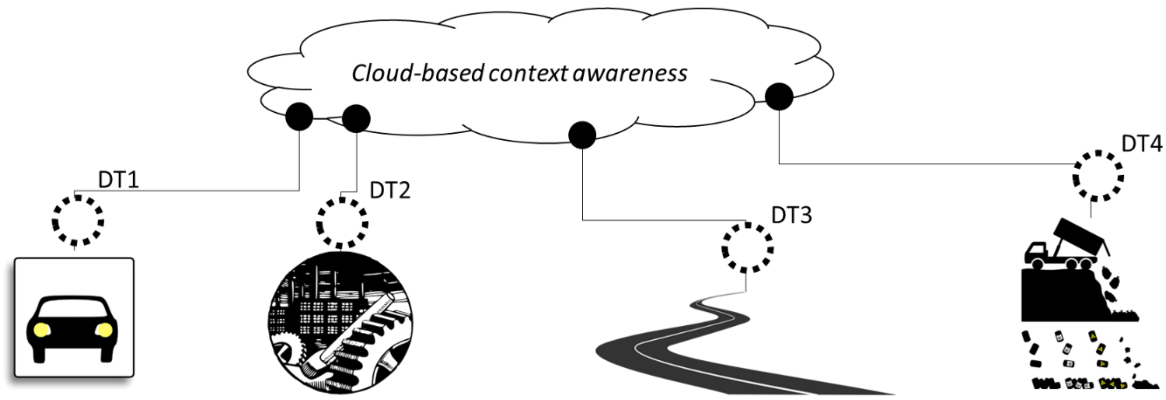

Fig. 1. Edge intelligence vs. Digital Twin Network: two different perspectives of context-aware manufacturing processes in the e-vehicles microfactory paradigm.

Figure 2 is such an example, implicating a flowchart, including also the information on what production modules are human-controlled. This offers appealing visualization and it facilitates the explicability of the changes that are about to take place. At the same time, metrics [18] can be integrated, even if they are not in their monetary form.

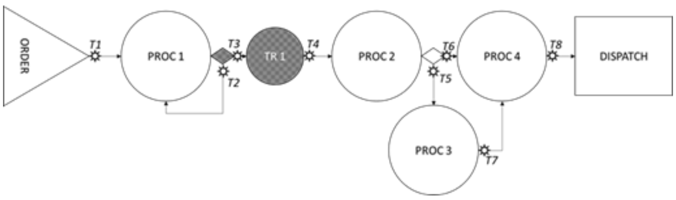

Fig. 2. Modelling a process: the modules are Processes and transportations. Rhombuses: decisions, Modules with pattern: human-based operations. Transactions *Tn* are also shown.

This could be done through the so-called function blocks [19], or object-oriented modelling [20] in any case. An interesting, yet heuristic, metric for the workflow could be the transactions taking place (denoted by *Tn* in Fig. 1) in order to verify that a resource and/or information exchange has taken place. This is highly convenient as the following issues are taken into consideration automatically:

- The KPIs-related information can be embedded, engaging the aforementioned sustainability into productivity, resulting in the set (time, social aspects, quality, flexibility, cost, resources, energy consumption, LCA related information) [21,22]
- The connectivity with other business functionalities can be represented up to a point (orders, resources management, sales, design)
- The efficiency of the changes can be studied (comparing different scenarios)
- The link to certification (involving Blockchain technologies and experts [23])
- The use of probabilities can be used to study the effect of strategies.

Regarding this latter aspect, judging by the modelling that occurred in the case of Fig. 1, the minimum transactions scenario in this case can be denoted by the group *{T1, T3, T4, T6, T8}*. This results in total 5 (sets of) transactions. A random scenario would be: *{T1, T2 x N, T3, T4, T5, T7, T8}* that is in total 5+*N*, *N*≥0. The probabilities distribution of the transactions is a characteristic that is of great importance, as it can be used to describe the efficiency of a strategy. I.e., utilizing theoretically a maximum entropy distribution, as in Fig. 3, one can conclude that the particular line is very hard to control successfully, and, probably, regardless of other KPIs, it needs to be modified.

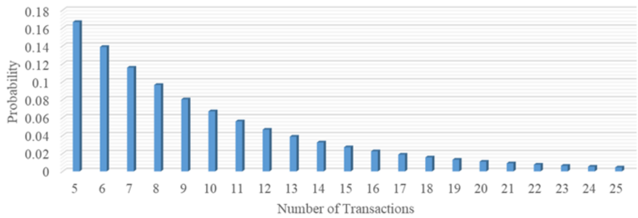

Fig. 3. A distribution of total transactions probability for the Fig. 1 scenario.

A modification is not a straight-forward, however. As seen in the case of Fig. 4, replacing Process #1 with an automated one that is driven by automated control, reduces the maximum number of transactions to 6, however, the manual operations are also reduced.

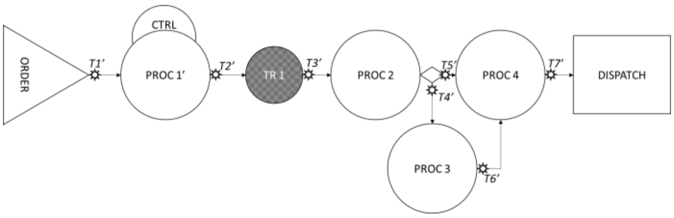

Fig. 4. Modelling the modified process sequence.

In the case where only one person was involved in all the manual operations, then this change may be characterized as "positive" (with respect to human inclusion). In the case two people were involved, then one person has to be redirected to another position.

2.1. Indicating causal relationships

The production KPIs, however, as well as their links [24], are not explicitly shown. In case one uses the case of object-oriented modelling, each transaction could conceal a packet of information. Besides sending signals about whether the operations have been fulfilled to a block-chain agent, additional information on production metric can be also communicated. In any case, the right amount of information abstraction and the adequate level of encryption can be utilized in order for the information to be kept private.

What would then be the next step is the quantification of the impact of a change in a workflow. This could be driven by innovation absorption, or digitalization in particular. To achieve this, one could engage all the potential transactions in one array (vector). Then, a matrix could link the transactions after the change, with the transactions vector before that, as per Eq. 1. Within that matrix, the ones denote a relationship, hence an involved cost. The zeros indicate independence. The most expected way to fill in this table is through a network of experts. This procedure renders it a heuristic modelling procedure, even though it can be performed either manually, or through Artificial Intelligence.

$$\mathbf{T}_2 = \begin{bmatrix} 1 & 1 & \cdots & 0 \\ \vdots & 1 & 0 & 0 \\ \vdots & \vdots & \ddots & 1 \\ 0 & 0 & \cdots & 1 \end{bmatrix} . \mathbf{T}_1 = \mathbf{A} . \mathbf{T}_1 \qquad (1)$$

These change can potentially denote cost. Therefore, some backtracking in lifecycle [6,26] could be provided, in order to be able to take into account all the CAPEX and the OPEX involved. There are also the additional KPIs that can be taken into consideration, that could potentially be transformed into monetary units, such as: time, quality, energy consumption, flexibility, amount of data utilized, social KPIs, training needs. Then, using an overall cost function, one could determine whether digitalization is profitable. It is noted that a square **A** matrix implies no change in the structure of the business.

2.2. The complexity of the network

The case of a microfactory is even more complex, as one is interested in reassuring that the investment is profitable. To this end, the whole network of engaged stakeholders should be engaged, as per Fig. 5, in which various indicative agents have been integrated. As a matter of fact, the whole value chain needs to be included, since, in the era of Industry 4.0, everyone is connected to everyone and Industry 5.0 requires also taking into account Human-Centered Cyber Physical Production Systems.

In this case, there are operations that are stochastically run, like maintenance, or even fetching resources from the warehouse. In the respective modelling, the corresponding probabilities may have to be included in the modelling so that the system is accurately represented. To this end, one needs (in a modest scenario) a common reporting/commanding system, a certification procedure, a common data model, common business objectives and potentially some sort of Query Language for Graphs towards optimization [27].

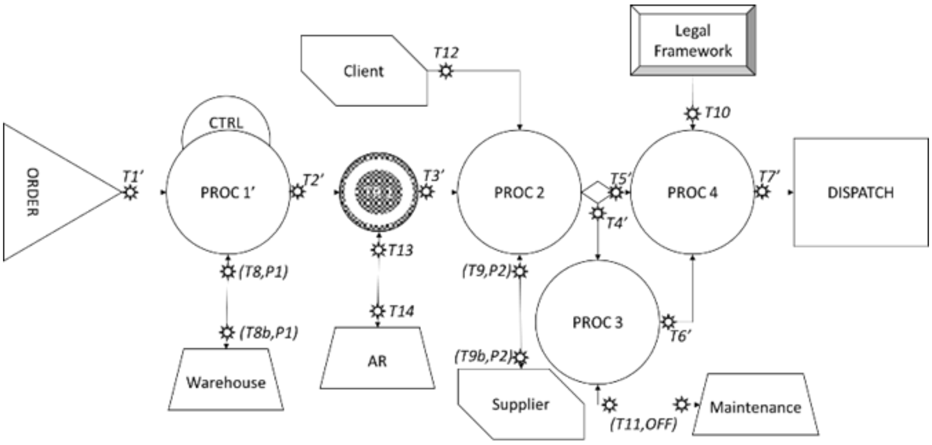

Fig. 5. Enriched graphs-based modelling of production, business and ecosystem.

2.3. Reporting through the digital twin

The role of digital twins in the smooth operation of such a line is crucial; they can facilitate addressing what-if scenarios but also be able to provide feedback to the process (Fig. 6) [27]). They can also help with reporting, by sharing information with the help of a Blockchain mechanism (Fig. 7). The existence of experts, though, is an open question, as physical certification is still to be addressed.

Fig. 6. Manufacturing Process Control through a digital twin: Selection of KPIs (top) and recommended Process Parameters (bottom).

As an extra operation, Explicable AI, in particular, can be used to train further the line operators / engineers. Thus, there are close interdependences in information exchanges (and thus induced costs), as foreseen by matrix modelling above. As a matter of fact, the link of business world with the technical (Digital Twin) world could be performed with the help of Blockchain's smart contracts (among others).

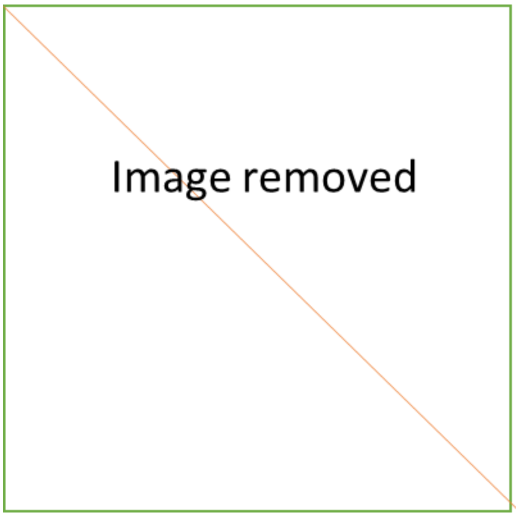

Fig. 7. Fetching Blockchain-shared records that have been registered by a manufacturing process digital twin.

2.4. Case study and Implementation

The current conceptual framework is discussed under the implementations made within AVANGARD project. Therefore, the implementations include a JAVA based Blockchain client, a python-based digital twin and a variety of digital tools, as they were implemented by the consortium [27-29]. The case of the automotive microfactory, in particular, is related to manufacturing e-vehicles [6].

3. Preliminary results & Discussion

For the case of a microfactory in the automotive industry [6], the numbers are highly interesting. In the current case, the involved entities are: one supplier, five stations within the microfactory, one external LCA expert, one welding certifier and 100 clients (minimum, per moth), plus the testing phase. Utilizing a linear scenario, without involving circular economy, the total number of transactions per month is

$$(100_{\text{clients}}) \text{ x } (1_{\text{LCA}} + 4_{\text{stations}} + 1_{\text{supplier}} + (1_{\text{welding}}+1_{\text{certifier}}) \text{ x } 30_{\text{parts\_welded}} + 1_{\text{testing}})=6700_{\text{sets of transactions}}$$

for a "transparent" scenario, where all the information is visible to the peers. Reserving a minimum of 10 KPIs for each station, with 4 Bytes each, the information is already substantial (approximately 3MB per year), yet the overall procedure is feasible.

The challenges, however, lie in the fact that the matrix of Eq. 1 is not fully known. There are usually no previous cases to compare to, and the subject is complex enough to contain aspects that almost no one could regard a few years ago, i.e. the connectivity between LCA and data preservation [30]. Hence, experts' networks are required in order to fully model such changes. However, it is of utmost importance that knowledge databases are created through practical cases of microfactories' operation and/or design.

3.1. Certification challenges

It is noted that, besides certification, data could be elaborated towards the direction of achieving dynamic, or even adaptive, LCA. As such, the workflows/networks can be extended with extra services. The update, however, of the databases is not straightforward, due to different users' rights.

An additional challenge would be the definition of the peers. The Blockchain can only guarantee the transactions through them. So there are two requirements to this end: a critical number of peers and a link to physical certification. The use of digital twin networks [29] could be adopted in such a case in order for the transactions to be automated.

As a result, besides involving physical certifiers – experts, authentication (in terms of physical implementation and not digital [29-31]) needs to be implemented. This way, by revealing a uniqueness characteristic of the measurements, the authentication can be achieved either through exploiting the nature of the measurements, or artificially (Fig. 8). A third way to achieve this could be the formation of an internet of trust [31-32]. This, on its own, has its unique, obvious challenges, that are not needed to be enlisted herein.

Additional technical obstacles, with respect to Blockchain itself, could be the demand for a number of validators [33], the danger of "51% attacks" [34] and time-restrictions, as new blocks may have to be formed every 10 minutes [35].

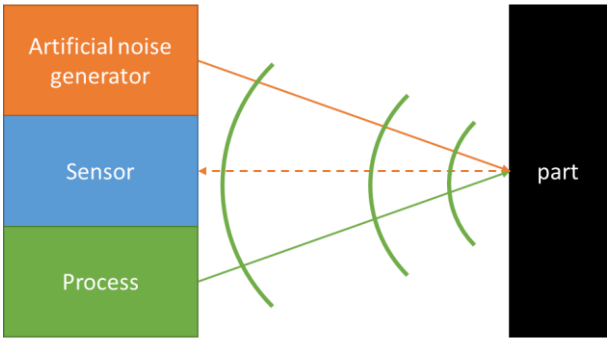

Fig. 8. Physical authentication of a measurement towards certification in manufacturing process characteristic monitoring. Characteristic can be quality, energy efficiency, resources utilization, etc.

3.2. Impact on communications

IIoT (in its literal sense) may be the missing link in all of these in the context of a digital twin network [36]. This implies that the use of a specific profile of 5G networks, i.e. the use of IPv6-based URRLC [37] may be highly useful in the near future, in cases of cloud-based process control. However, the need for edge intelligence does not necessarily imply the need for communications in a direct way. A sophisticated, yet arbitrary, characterization of manufacturing process digital twin operations can be seen in Fig. 9.

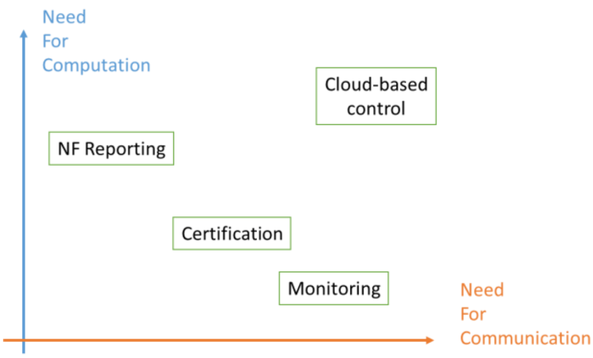

Fig. 9. Arbitrary positioning of four digital twin network operations in two axes. All three of them potentially require edge intelligence.

4. Conclusions & Future Outlook

As seen above, the digital twins' integration, as part of a digital transformation has various repercussions at business level, including the need for transactions modelling, sustainability and productivity related KPIs integration in them and networking at both physical and cyber level. The current metamodelling seems promising in being able to capture the needs for all the above in a heuristic manner, potentially with the help of human intervention and AI. This extends the capabilities for minimizing upfront investment in the case of innovation absorption.

Additionally, it is of major importance that there is communication between the various digital decision points. This implies that there are even more transactions between the process and various manufacturing agents, such as suppliers, training providers and clients. In order for this communication to be performed automatically, the digital twins need further elaboration with respect to their architecture as well as the data abstraction mechanisms that they carry.

However, all these are far from final. Regarding future work, elaborating metamodelling and KPIs retrieval in an automated fashion is required. Additionally, the introduction of Key Variables [22] could be extended towards financial and business aspects.

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Appendix A. Graphs entropy

In this work, the transactions are used as a measure of complexity. Linking to graphs entropy, extra added value on elaborated metrics could be achieved; in particular, structural complexity [38] could be utilized to this end. Complex values could also be highly useful in the context of Product-Service Systems (equivalently, vectors in literature [39].

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