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A two-stage decision support system for manufacturing processes integration in microfactories for electric vehicles

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Abstract

Integrating a manufacturing process is not a straightforward decision. Involved cost models are complex covering the whole lifecycle of the part in the context of circular economy. In this work, given the complexity of circular industry and the modularity required in the case of electric vehicles, a framework for a dedicated decision support system is presented. A case study for a microfactory is presented. The two stages of the decision-support system (DSS) are applied, with the first one proving empirically the feasibility of the technology integration and the second one involving a detailed cost model for assessment of the return of investment (ROI).

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Keywords: Process Integration; Decision-support system (DSS); Microfactory; Manufacturing; Cost-modelling

1. Introduction

The microfactory has been recently defined as the manufacturing plant in cellular layout with the integration of new innovative processes (i.e., additive manufacturing, laser welding/cutting), supporting the customization with ease configuration, requiring lower capital investment and energy demands, occupying a fraction of the shop-floor area in comparison with actual production, producing lower carbon emissions and providing a reduced delivery time to the customer due to the pull architecture [1]. Also, the term in the literature may often refer to the miniaturization of the machine, such as micro-lathe and the micro-assembly of the sub-products [2].

Hereafter in this study, the first definition is utilized. The advantages of microfactory consist from the pull manufacturing strategy in which the production begins when the order registered by the end user, with the customer preferences, in contrary with the push strategy which mass production is done [3]. This strategy concludes to a lower time-to-market. It is also noted that the current manufacturing production usually emits higher carbon emission to the environment. Furthermore, the most crucial deciding-factor is the capital expenditure of the plant, as the microfactory aims at minimizing the cost of a fraction of the investment with the mega-factory. The upfront investment for the building of plants costs approximately $2 to $4 billion from paradigms of leading companies in electric vehicle (EV) production [4,5], while the microfactory concept required a fraction of this cost, approximately to $46 million [6].

Hence, the cost-modelling of such as investment requires decision-support system (DSS) tools. This study employs a

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two-stage DSS on the proper assessment of return of investment (ROI) for a laser-welding system into microfactory's EV plant. The first state determines if the integration of such system is possible, while the second one consist from the detailed cost-modelling. Both of the stages are evaluated by two different experts' perspectives, the microfactory and the Original Equipment Manufacturing (OEM), utilizing experts' knowledge on both the weights and the heuristic values.

2. State of The Art

The proper process selection is crucial for the sustainability of the firm regarding the three pillars; environmental, economic and social. The key-driver of the selection is the need for transition from the linear "take-make-dispose" to circular economy strategies [7]. New criteria should be integrated to the traditional ones for a holistic approach for the selection of sustainable process, such as the initial cost/capital expenditure (i.e., the purchase of the machine, tools, materials, etc.), the operational expenditure (i.e., the maintenance, the material (stock and scrap/wasted), required energy, labor, primary and auxiliary machine expenses, jigs and fixtures for the machine and so [8]. Another important aspect is the new functionalities that may be integrated into the new production towards zero-defect-manufacturing, concluding also to an environmental-friendly production [9]. Such functionalities may need extra resources, ranging from smart industrial sensors to actuators, interconnected through Digital Twin architecture for the optimal monitoring of the energy and waste during the operation.

New aspects are thus inserted into the cost-modelling regarding the environmental impact of the suitable process/machine which may increase the actual total price due to extra equipment, while achieving the target of 20% reduction and enhance the energy efficiency at a minimum rate of 32.5%, with 2020s levels, by 2030 regarding the EU climate and energy law (2030 Framework) [10].

In the literature, the most common approaches for the selection of process are 1) analytical, 2) probabilistic, 3) knowledge base system, 4) manufacturing and product complexity, 5) methodological, 6) optimization algorithms and 7) topological [11] while multi-criteria techniques such as Analytical Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and VIKOR are widely used in industry [12] or combination of those [13]. Breaz et al. [14] conduct a study for process selection between two subtractive and one additive manufacturing operations by utilizing an integrated multi-criteria decision-making algorithm of AHP and fuzzy approach. Desai et al. [15] implement AHP for a cyber design for manufacturing (DFM) for the optimal selection of both materials and processes. The authors in [16] developed a decision support tool for the proper selection among four additive manufacturing processes based on traditional criteria, such as quality, build-up time and environmental related such as carbon emission. Omar and Soltan [17] investigated the best candidate welding process based on two stage approach, a fuzzy-AHP and a fuzzy-TOPSIS method by determining economic, process and product factors. Cunningham et al. [18] investigated the cost modelling based on direct and indirect costs of the wire-arc additive manufacturing operation. Busachi et al. [19] explored alternative methods for the cost estimation in additive manufacturing (AM). Similar to that research focus, NIST thorough investigate the direct and indirect cost on AM production [20].

In the Industry 4.0 context, circular economy (CE) strategies could accelerate the development of microfactory concept [24], as microfactories could be characterized as decentralized manufacturing plants. A comparison between centralized and decentralized automotive plants has been conducted by Mourtzis et al. [22] assuming the same highly demand of customization preferences of vehicle component, concluding to slightly better cost and lower environmental impact utilizing an exhaustive search algorithm.

The adoption of such CE strategies should enhance the efficient of energy (MJ), carbon footprint (kg CO_2) and waste disposal (kg) [23]. However, the trade-off between cost and the environmental impact of new sustainable products is still challenging [24].

The cost modelling is a comprehensive, yet complex procedure due to the number of the available dependable variables for the decision-making resulting to best candidate. At the process level, a plethora of criteria exist, as come across in literature above. They are enlisted in the Table 1, grouped into four main groups. Every single aspect of product and production lifecycle are considered, as the concepts of profit and Return-of-Investment have to be generalized in order to take into account every single factor introduced by technology integration.

Table 1. Cost list.

Cost-related Group	Description
Capital Expenditure	• Purchase of the machine • Training of the personnel • Training for "Expert Agent's • Innovated-related equipment that leads to extra profit • Zero-defect-manufacturing related process and functionalities • Development of Digital Twin, including sensors, actuators and cost of simulation software • Payback time
Operational Expenditure	• Labor cost (i.e., operation, inspection, etc.) • Energy consumption (kWh) • Time of usage (idle, machining) • Machine consumption • Scrap/part • Penalty of Change (due to Market Share Increase) • Penalty of Change (Flexibility due to electric vehicles personalization)
End-of-Life/Disposal	• Resale • Scrap
Circular Economy-related cost	• National penalties • EU penalties

3. The methodology

The decision support system is formulated into two steps, with the first one checking through the feasibility ~~the~~ through a heuristic evaluation and the integration of the reliability of the expert agents that are used to this end. The second step integrates the cost model regarding both the part and the machine life-cycle, and the implementation of the circularity of the method into industrial application. Figure 1 illustrates the DSS approach for the cost modelling of the manufacturing process. A detail is given in Fig. 2 regarding the uncertainty introduced artificially to avoid bias in the estimations.

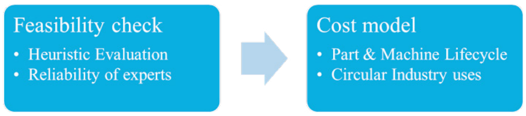

Fig. 1. A two-step approach

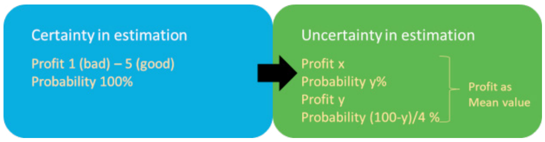

Fig. 2. Step 1 detail: the rationalization of the heuristic profit

In the first step, the feasibility check considers the opinions of different experts. The estimations can be done naively, simply by fusing the criteria in a linear way and leading to a certain outcome, taking into account that the probability for these values is definite. However, there is a case that the profit is not that fixed, as there are five stages ranging from 1 (very bad) to 5 (very good) with a probability distribution. The second estimation deals with this uncertainty, assigning a probability in each one of these cases. The characteristics of this probabilistic heuristic approach for the profit are depicted in the Figure 2.

In any case, if both estimations lead to positive results, taking into account a mean value across the validity of the experts, then it is probably worth integrating the process and the second part of the analytical cost modelling can take part.

In the second step, the experts take into account all the costs deriving from the lifecycle, as illustrated in Fig. 3. Their cost models have once again been fused, while instead of weights for each one of the costs, the probabilities are taken into account (i.e., for the purchase of the machine, the price is 100% going to be paid).

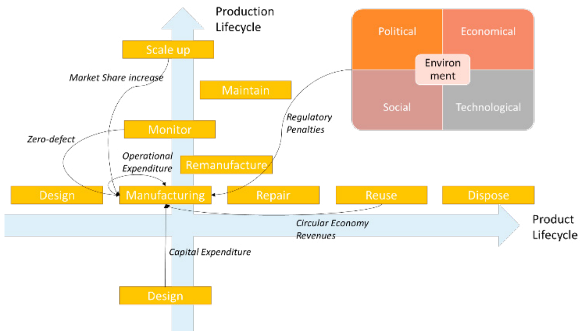

Fig. 3. Step 2 detail: Cost Mapping Procedure

It is noted that this framework can be used either for accepting/rejecting suggestions, or for selecting the appropriate alternative among many different ones.

4. Implementation

The platform used to support this procedure has been implemented in JAVA language, exploiting web services and representational state transfer (REST) application programming interface (APIs). The main driver is the user, who is either the expert (Fig. 4), setting the weights and the values or the moderator who has set the problem. These two activities are illustrated in Figures 5 and 6, respectively.

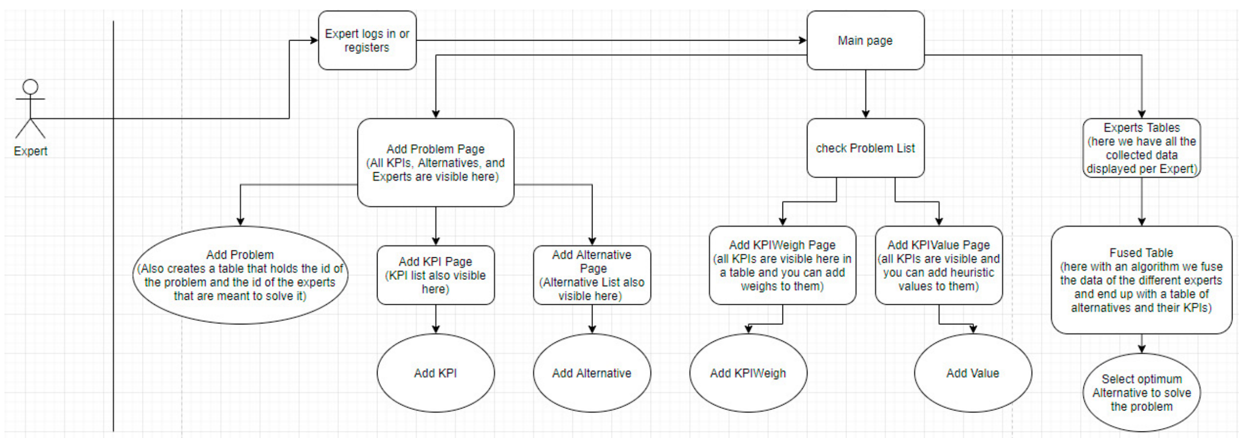

Fig. 4. The procedure as an activity diagram (implementation in JAVA)

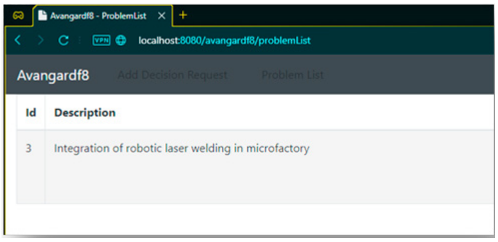

Fig. 5. The screen of defining a problem

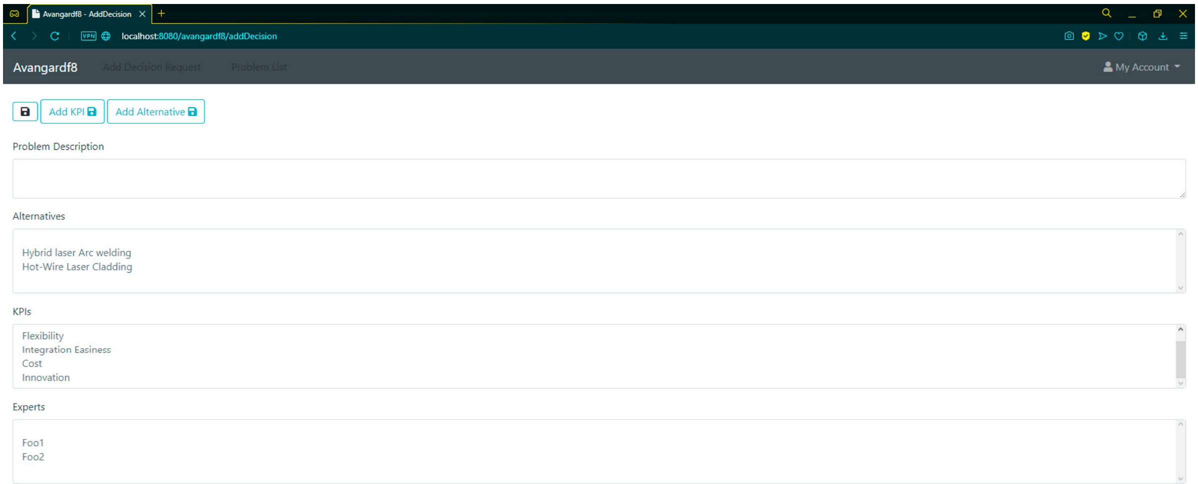

Fig. 6. Sample screen of expert voting

5. Case study and results

The case study that is investigated hereafter is the integration of laser welding in an automotive microfactory. This case study is very indicative of a technology or process integration, as frugality, glocality, personalization (Fig. 7), as well as certification and sustainability criteria dictate the use of specific performance indicators.

To harmonize these indicators, as mentioned in the methodology section, the "Heuristic value" is the profit, in the generalized sense. Thus, tables 2 and 3 describe the values from the perspectives two experts; one from the microfactory and one from the OEM, whereas two experts may assign different criteria, different criteria weights and different criteria values.

The heuristic (Likert) scale has been defined hereafter as following: 1 – very bad, 2 – bad, 3 – neutral, 4 – good, 5 – very good (profitable). Only a fragment of all the factors being introduced has been mentioned, as the scope of this work is to point out the applicability of the method.

Table 2. Expert 1 table (from microfactory).

Criterion	Weight	Heuristic Value
Flexibility	0.3	4
Cost	0.4	2
Integration Easiness	0.3	2

Table 3. Expert 2 table (from OEM).

Criterion	Weight	Heuristic Value
Flexibility	0.6	4
Cost	0.2	2
Innovation	0.2	5

Afterwards, the heuristics values are rationalized as shown in Tables 4 and 5. The values are being changed according to the rule that each heuristic value has a specific distribution; herein, 60% has been considered to be the probability for the selected values, while for the rest of the values a uniform distribution has been considered. Thus, extreme values are being moved to more conservative ones.

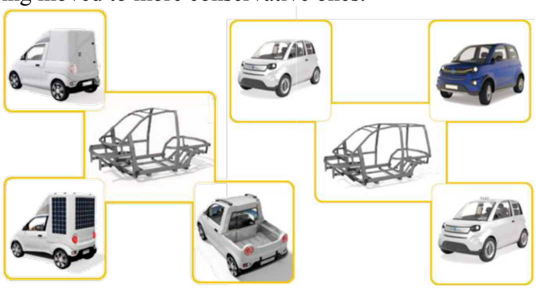

Fig. 7. Electric vehicle configurations

Table 4. Expert 1 normalized table.

Criterion	Weight	Heuristic Value
Flexibility	0.3	3.5
Cost	0.4	2.5
Integration Easiness	0.3	2.5

Table 5. Expert 2 normalized table.

Criterion	Weight	Heuristic Value
Flexibility	0.6	4
Cost	0.2	2.5
Innovation	0.2	4

Then, the total heuristic profit is calculated as the sum of the products of criterion and the heuristic value as depicted in the Table 6.

Table 6. Experts normalized overview.

Criterion	Expert 1	Expert 2
Heuristic Profit	2.8	3.7

Given the fact that the two experts have different origins, their opinions/perspectives may be biased. Table 7 depicts the normalized data for the fused heuristic profit, implying the integration of both experts into a single decision variable. The first column states the weight of the first expert, leading to a different fused heuristic profit.

Table 7. Experts normalized table.

Weight of Expert 1	Fused Heuristic Profit
0	3.7
0.1	3.61
0.2	3.52
0.3	3.43
0.4	3.34
0.5	3.25
0.6	3.16
0.7	3.07
0.8	2.98
0.9	2.89
1	2.8

Hence, the average fused heuristic profit equals to 3.25 in the case of a uniform distribution of the weights. This is the case where every scenario of experts' bias is considered to be plausible. For reasons of safety, a subjective scenario is also used, providing a fused heuristic profit of 3.162. The distribution used in this case is a triangular one, with the maximum probability set at weight for expert 1 equal to 0.8.

This study assumed the integration of the laser welding with a capital cost of 60,000 euros. The viewpoint of the microfactory expert focuses on the ease of this kind of integration to the current shop-floor while the OEM perspective on the innovation strategy such as the market share and the maintenance cost. Both agents introduced flexibility as a criterion, however each one assumed different weight. All the aforementioned criteria and weights are described in the Table 8 and Table 9, where the monetary values are presented given that the amounts have been distributed in the first three years of the new microfactory operation. The monetary values have been defined by the same experts in this case.

Table 8. Expert 1 Profit table.

Criterion	Probability	Profit (€)
Flexibility	0.7	20000
Cost	1	-20000
Integration Easiness (Need for purchase of IT Infrastructure)	1	-10000

Table 9. Expert 2 Profit table.

Criterion	Probability	Profit (€)
Flexibility	0.9	30000
Cost	1	-20000
Innovation (Market share increase)	0.1 (very conservative)	100000
Innovation (Maintenance Cost)	0.7	15000

The total profit according to the microfactory agent equals to a negative value of -16,000 euro while the OEM calculated at 27,500 euros. Then, what is determined is the "Fused Monetary Profit" by varying the weight of the first agent. This is shown in Table 10.

It can be easily observed that profits due to zero defect manufacturing or zero waste manufacturing have been neglected; they would need much more elaborated estimations and/or models, exceeding the purposes of the current study. Energy consumption has also been omitted as operation cost, since the case of laser welding could lead to more green manufacturing in the case where the part can be redesigned to have fewer welds. However, this would render the current proof of concept extremely complex. On the other hand, increase in the sales as well as easiness in change of production have both been considered, even in a mostly conservative manner.

Table 10. Experts normalized Profit.

Weight of Expert 1	Fused Monetary Profit (€)
0	27500
0.1	23150
0.2	18800
0.3	14450
0.4	10100
0.5	5750
0.6	1400
0.7	-2950
0.8	-7300
0.9	-11650
1	-16000

Thus, assuming a mean value along this table, the final profit with the integration of the two distinguish expert agents of different observant view concludes to a positive value:

- Average Fused Profit = 5750 €
- Subjective Average Fused Profit = 2456 €

It is noted that the above values regard profit per year in the worst case scenario of properly operating only during the first three years.

6. Conclusions

This research work proposed a two-step approach decision support system for the cost estimation on the integration new machinery such laser welding into modular microfactory design based on distinct individuals (experts); belonging either to the production personnel of the microfactory, or to the OEM. Firstly, an integrated "Heuristic profit" is computed taking into account various criteria that is able to successfully act as an integration feasibility metric. Then, the exact expected monetary profit from this integration is estimated, leading to a decision under the strategy of Industry 4.0 and Circular Industry. This method seems straightforward and rather complete with respect to existing methods. Furthermore, it is in accordance with Product-service systems and digitalized decision making systems. Finally, it is extensible, implying connectivity with software modules running elaborated cost models.

Regarding the integration of the laser welding technology into the microfactory itself, it seems that its circular use, even with these rough estimations and with a rather large amount of uncertainty inserted into the system, seems to be profitable. Both digitization and sustainability, in any case, seem to be of major importance to this integration, i.e., due to IT infrastructure needed for quality assessment, etc.

As future work, it is strongly recommended to include more experts, further aspects of lifecycle into cost and narrow down the uncertainty and the bias of the experts, leading to a more exact model.

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