Developing a Manufacturing Process Level Framework for Green Strategies KPIs Handling

Vasiliki C. Panagiotopoulou, Alexios Papacharalampopoulos, and Panagiotis Stavropoulos(✉)

Laboratory for Manufacturing Systems and Automation, University of Patras, 26504 Patras, Greece
pstavr@lms.mech.upatras.gr

Abstract. Green strategies in manufacturing have multifold perspectives implying that are highly diversified in terms of resources management. Popular green strategies are Zero Defect, Circularity and Sustainability. The challenges regarding resources efficiency result from different concepts addressed by each strategy; Zero Defect focuses on defect prevention via quality planning, control, and improvement, while Circularity addresses resources optimisation via resources management, material production, usage and disposal. Sustainability is a different approach, to include economic growth and social impact, besides resources management, waste management and environmental impact. Until now, key performance indicators (KPIs) have been used for individual strategy, while literature shows a lack of frameworks towards transforming KPIs when adopting more than one strategy. The current work is a step towards defining an approach describing the relationship between the KPIs of different green strategies and elaborating the repercussions of this transformation on workflows and specifically on manufacturing processes. Two different approaches could be used (monetary and qualitative) with thermoforming used as a case, and the results are indicative of the method efficiency, where KPIs for Zero Defect, Circularity and Sustainability are compared. The framework is developed to be later generalised and applied to other manufacturing processes.

Keywords: KPIs · Green Strategies · Zero Defect Manufacturing · Circularity · Sustainability

1 Introduction

Manufacturing is heavily contributing to carbon emissions in Europe, being the second top contributor behind the energy sector. Since EU has developed a roadmap to gradually decrease its carbon emissions until becoming the first carbon neutral continent by 2050 (Green Deal), the industrial sector has to keep up with massively reducing its energy consumption and carbon footprint [1, 2], to contribute to this initiative. Several green strategies have been developed over the last few decades but in this work, the focus is on zero defect manufacturing, circular economy and sustainability since these strategies have been extensively developed and are trending approaches in innovation and industry.

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Zero Defect Manufacturing is the extension of the widely adopted 6-sigma approach, focusing on eliminating the number of defect products [3], while approaches focusing on circularity aim to transform linear economy currently used (production, use, disposal) into a circular economy where products are reused, recycled and repurposed [4]. Sustainability is a more general approach, focusing on planet, people and economics, in order to provide the best solutions with low environmental impact, taking into consideration the welfare of workforce and society and ensuring profit for companies [5].

Literature search regarding reported KPIs (Table 1) on zero defect manufacturing (ZDM), circular economy (CE) and sustainability (S) was performed, with the most commonly used KPIs summarized in the following table. KPIs are categorized in three main categories: 1) environmental, where use, waste and emissions are included, 2) financial, where quality, cost, delivery and flexibility are included and 3) social, where community, employees and suppliers are included. The main limitation was that these KPIs were solely used for the purpose of a single green strategy, without defining what may be the impact of one KPI if used in additional strategies, which may well be contradictory from one green strategy to another. Current work is aiming to develop and propose a framework on the relationship between KPIs for green strategies.

Table 1. List of KPIs per category (environmental, financial and social aspects) and allocated per green strategy (zero defect manufacturing- ZDM, circular economy-CE, sustainability-S)

Categories	KPIs	ZDM	CE	S
Environmental	Material consumption [6, 7, 8, 9]		X	X
	Water consumption [7, 8, 10]		X	X
	Energy consumption [6, 7, 8, 10, 11]		X	X
	Use of renewable energy [7]		X	
	Energy efficiency [7]		X	
	Increase recycling rate [6, 9]		X	
	Waste generated [6, 10]		X	X
	Reduce carbon emissions [9, 11, 12]		X	X
	Reduce disassembly time [9]		X	
	Fuel consumption [8, 11, 12]			X
	Water and land emissions [12]			X
	Wastewater [10, 12]			X
Financial	Parts per month [13]	X		
	Tardiness [14, 15]	X		
	Defects ratio [15, 12]	X		
	Scrap and Rework [16, 12]	X		X
	Average production cost [14, 15]	X	X	X
	Delay cost [14, 15, 7, 8, 11]	X	X	X
	Final unit cost [15]	X		

(*continued*)

Table 1. (*continued*)

Categories	KPIs	ZDM	CE	S
	Maintenance cost [15]	X		
	Learning cost [7]		X	
	Inventory cost [8, 11]			X
	Product reliability and durability [12]			X
	Overhead cost [12]			X
	Cycle time and flexibility [12]			X
	New product development [12]			X
Social	Occupational health & safety[8, 11, 12]			X
	Training and education [8, 11, 12]			X
	Job satisfaction and salary level [12, 10]			X
	Supplier certification &commitment [12]			X
	Gender equity [8]			X
	Benefits/commission/profit [10]			X
	Society and Human rights[17]			X

2 Framework

There are in principle two main approaches towards comparing the effect on adopted strategies on resulting optimization. The first one would be to compare everything in terms of monetary units. However, this would require elaborated financial models [18]. Herein, an alternative way of achieving this is attempted, taking advantage of a qualitative comparison. This qualitative approach proposed aims to identify the correlation between the different KPIs of the most used green strategies. This framework starts off with identifying (1) the manufacturing process that will be used as a case, (2) the materials that will be used as an input and (3) the final product. The selection of the above-mentioned parameters will dictate the parameters that will be used in the process. Then, the relevant KPIs per green strategy will be selected, ideally using a database such as Table 1. Following the KPI selection, the process parameters that are impacting the KPIs will be defined, followed by the determination of the relations between parameters and KPIs. The ultimate objective is to check whether all the KPIs, in pairs, have a good correlation. Equivalently, the change of the KPIs with the modification of the Process Parameters has to be of the same trend (monotonicity). If this is the case, then the strategies can be used interchangeably, as in the case 1 of Fig. 1, where an exemplary schematic is presented with different relationship types between KPIs and their respective process parameter level.

3 Case Study

In this paper, thermoforming of low density polyethylene into a hemispherical shell was used as a case study. Data were collected from a template case study consisting of

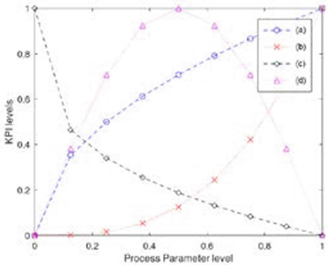

Fig. 1. KPIs relations: Case 1 - (a) and (b), Case 2 - (a) and (c), Case 3 - (a) and (d).

a single process with process speed being estimated at 140 s, with 60 kWh for a full hour operation of the thermoforming equipment. The material used for the production of bowl was either raw low density polyethylene (0.88g/cm^3) or recycled polyethylene. The final product would have been a hemispherical shell, of 5 cm external radius and 4.5cm internal radius. Values for the respective parameters were calculated from the previously described process parameters. The green strategies used for this case study were zero defect manufacturing, circular economy and sustainability, with the main KPIs found in Fig. 2.

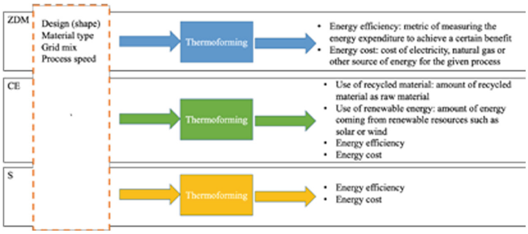

Fig. 2. Relevant process parameters (left) that affect KPIs (right) per green strategy.

4 Results

Thermoforming was used as an example because of its great environmental impact, the majority of which derives from the use of electricity, as shown in Fig. 3. The environmental impact of thermoforming was calculated from SimaPro 9.3.03 and Ecoinvent Database 3.1.

In the qualitative approach, the relationship between the process related parameters and the KPIs were investigated, determining a relationship between the following pairs:

1. Material type used (mass of recycling material as raw material) and recycling rate: applicable pair for circular economy, showing a linear relationship (Fig. 4)
2. Design as in shape and mass of material used and energy efficiency: pair applicable to sustainability, showing an exponential relationship, with energy efficiency decreasing as the mass of raw material increased (Fig. 5)

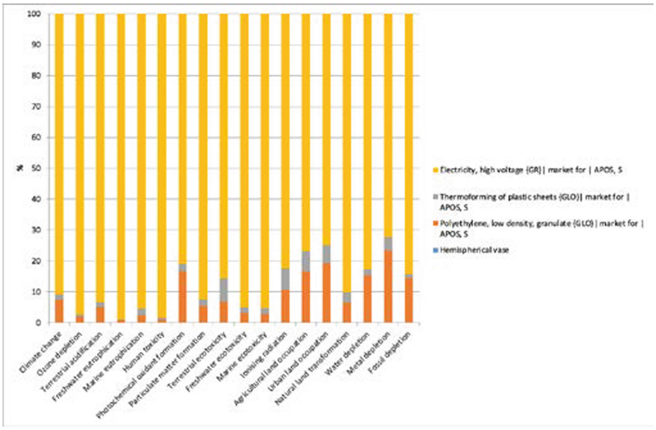

Fig. 3. Environmental impact of thermoforming after performing LCA using SimaPro, in categories such as climate change (carbon footprint and more), human toxicity, fresh water, marine ecology.

3. Percentage of renewable energy used and energy cost: pair applicable to sustainability. The relationship though is not linear for all types of renewable sources due to high differences in value of different energy mixes (Fig. 6)
4. Process speed and energy efficiency: a pair applicable to all three green strategies, without a linear relationship since energy efficiency for thermoforming depends on both power of thermoforming and mass of material to be thermoformed (Fig. 7)

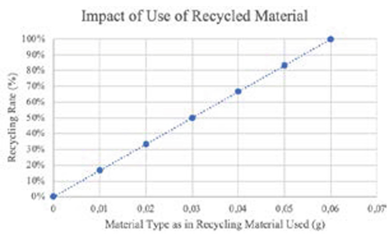

Fig. 4. Impact of use of recycled material on the recycling rate.

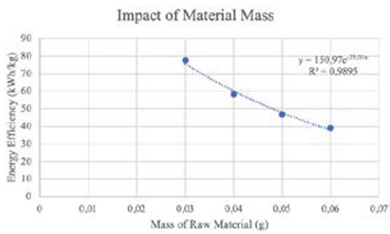

Fig. 5. Impact of raw material mass on the energy efficiency.

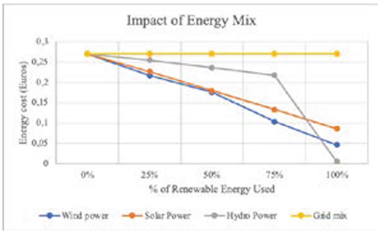

Fig. 6. Impact of energy mix on the energy cost in euros.

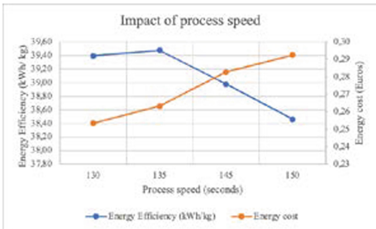

Fig. 7. Impact of process speed on the energy efficiency and the energy cost.

5 Discussion

This study has shown that the relationship between process parameters and KPIs in green strategies is not a straightforward and monotonous relationship for all cases, but it is rather determined by the selection of values per process parameters. This highlights the difficulty in harmonizing the KPIs in order to address multiple green strategies at the same time using unified approaches for process parameters optimization.

Design, in terms of shape or material weight, affects energy efficiency of thermoforming. However, this particular process is often disregarded when zero defect manufacturing is the green strategy of choice, but it is used for sustainability approaches where redesign using fewer resources is a key approach. The applicably of this parameter is not discussed in zero defect manufacturing despite its potential impact on the product being conformed with certain specifications. Similarly, using fewer resources should be linked to circular economy, but this relationship should follow the one described in this case. The type of material used, and especially the use of a percentage of recycled material instead of completely raw material, is often associated with circular economy as an approach to reuse, recycle and repurpose products. This, however, may have an impact on the features of the final product, as recycled material may not have the same properties as raw materials due to them being already processed and used in previous applications. Renewable energy used is linked to sustainability, as an effort to move from fossil based energy to renewable types of energy, such as wind, solar and hydropower. The relationship between percentage of renewable energy used and energy cost is not linear, and it is uncertain how this relationship is translated in the case where either circular economy or zero defect manufacturing is the green strategy of choice. Process speed is a process parameter related to zero defect manufacturing as a valuable parameter related to the quality of the final product and the defects ratio. However, an optimal value for process speed should be defined in order to have the best quality of the final product and the small number of defected products. In the case of circular economy and sustainability, increased process speed means increased energy consumption and cost, and potentially impacting workforce.

The main limitation of this framework is the fact that its applicability to other cases has been investigated. In addition, it has not been considered to use a weighted version of framework to include all aspects (environmental, financial and social KPIs). Greens strategies.

6 Conclusions and Future Outlook

Developing a framework to identify the relationship between process parameters and KPIs per green strategy has suggested that the relationship is far more complicated than thought, while extrapolating from one green strategy to another is not a straightforward process. The three different strategies have a different focus, with ZDM focusing on part performance, CE on resources efficiency and S on perpetuality of profit; often all these are being contradictive, albeit occasionally they all imply environmental constraint. Each green strategy has its own KPIs, and its own relationship between process parameters and KPIs, often contradictory, or worse; of different trend, between the different strategies.

Future work should focus on identifying the exact relationship between the different green strategies and their KPIs. In addition, the unification of the green strategies needs to be addressed, potentially through a hierarchical approach, taking into account the different cases of design and operation.

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References

1. Panagiotopoulou, V.C., Stavropoulos, P., Chryssolouris, G.: A critical review on the environmental impact of manufacturing: a holistic perspective. Int. J. Adv. Manuf. Technol. **118**(1–2), 603–625 (2021). https://doi.org/10.1007/s00170-021-07980-w
2. Stavropoulos, P., Panagiotopoulou, V.C., Papacharalampopoulos, A., Aivaliotis, P., Georgopoulos, D., Smyrniotakis, K.: A framework for CO2 emission reduction in manufacturing industries: a steel industry case. Designs (Basel) **6**(2), 22 (2022)
3. Papacharalampopoulos, A., Stavropoulos, P., Petrides, D.: Towards a digital twin for manufacturing processes: applicability on laser welding. Procedia Cirp **88**, 110–115 (2020)
4. Sassanelli, C., Rosa, P., Rocca, R., Terzi, S.: Circular economy performance assessment methods: a systematic literature review. J. Clean. Prod. **229**, 440–453 (2019)
5. Fysikopoulos, A., Alexopoulos, T., Pastras, G., Stavropoulos, P., Chryssolouris, G.: On the design of a sustainable production line: the MetaCAM tool. In: ASME International Mechanical Engineering Congress and Exposition, vol. 57588, p. V015T19A015 (2015)
6. Ahlers, R.: The life cycle performance assessment (LCPA) methodology. In: Rosa, P., Terzi, S. (eds.) New Business Models for the Reuse of Secondary Resources from WEEEs. SpringerBriefs in Applied Sciences and Technology, pp. 81–96. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-74886-9_7

7. Ávila-Gutiérrez, M.J., Martín-Gómez, A., Aguayo-González, F., Córdoba-Roldán, A.: Standardization framework for sustainability from circular economy 4.0. Sustainability **11**(22), 6490 (2019)
8. Amrina, E., Vilsi, A.L.: Key performance indicators for sustainable manufacturing evaluation in cement industry. Procedia Cirp **26**, 19–23 (2015)
9. Kanellou, E., Alexakis, K., Kapsalis, P., Kokkinakos, P., Askounis, D.: The DigiPrime KPIs' framework for a circular economy transition in the automotive industry. Procedia Manuf. **54**, 302–307 (2021)
10. Helleno, A.L., de Moraes, A.J.I., Simon, A.T.: Integrating sustainability indicators and Lean manufacturing to assess manufacturing processes: application case studies in Brazilian industry. J Clean Prod. **153**, 405–416 (2017)
11. Amrina, E., Ramadhani, C., Vilsi, A.L.: A fuzzy multi criteria approach for sustainable manufacturing evaluation in cement industry. Procedia CIRP **40**, 619–624 (2016)
12. Amrina, E., Yusof, S.M.: Key performance indicators for sustainable manufacturing evaluation in automotive companies. In: 2011 IEEE International Conference on Industrial Engineering and Engineering Management, pp. 1093–1097 (2011)
13. Steringer, R., Zörrer, H., Zambal, S., Eitzinger, C.: Using discrete event simulation in multiple system life cycles to support zero-defect composite manufacturing in aerospace industry. IFAC-PapersOnLine **52**(13), 1467–1472 (2019)
14. Psarommatis, F., Kiritsis, D.: a hybrid decision support system for automating decision making in the event of defects in the era of zero defect manufacturing. J. Ind. Inf. Integr. **26**, 100263 (2022)
15. Psarommatis, F., May, G., Kiritsis, D.: Predictive maintenance key control parameters for achieving efficient zero defect manufacturing. Procedia CIRP **104**, 80–84 (2021)
16. Martinez, P., Al-Hussein, M., Ahmad, R.: A cyber-physical system approach to zero-defect manufacturing in light-gauge steel frame assemblies. Procedia Comput. Sci. **200**, 924–933 (2022)
17. Saxena, P., Stavropoulos, P., Kechagias, J., Salonitis, K.: Sustainability assessment for manufacturing operations. Energies (Basel) **13**(11), 2730 (2020)
18. Stavropoulos, P., Papacharalampopoulos, A., Michail, C., Vassilopoulos, V., Alexopoulos, K., Perlo, P.: A two-stage decision support system for manufacturing processes integration in microfactories for electric vehicles. Procedia Manuf. **54**, 106–111 (2021)