ASSESSING THE SUSTAINABILITY OF MANUFACTURING PROCESSES IN THE MANUFACTURE OF TRANSPORT EQUIPMENT, BASED ON FUZZY GREY RELATIONAL ANALYSIS

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ABSTRACT

This paper presents a sustainability assessment of manufacturing processes for transport equipment, using fuzzy grey relational analysis. The metrics or sub-indicators for sustainability indicators and their relative applications in the manufacturing processes are used to create sustainability matrices, which are then compared with an ideal series in order to determine grades for the processes using the grey relational model. Grades in the form of values are determined for the performances of the manufacturing processes of four different kinds of transport equipment. The grades identified manufacturing processes in which the performance of the sustainability indicators could be improved.

OPSOMMING

Hierdie artikel bied 'n volhoubaarheidsevaluering van vervaardigings-prosesse vir vervoertoerusting aan, deur gebruik te maak van wasige grys relasionele analise. Die maatstawwe of sub-aanwysers vir volhoubaarheidsaanwysers en hul relatiewe toepassings in die vervaardigingsprosesse word gebruik om volhoubaarheidsmatrikse te skep, wat dan met 'n ideale reeks vergelyk word ten einde grade vir die prosesse te bepaal deur die grys relasionele model te gebruik. Grade in die vorm van waardes word bepaal vir die prestasie van die vervaardigingsprosesse van vier verskillende soorte vervoertoerusting. Die grade het vervaardigingsprosesse geïdentifiseer waar die prestasie van die volhoubaarheidsaanwysers verbeter kan word.

1 INTRODUCTION

The importance of a well-structured transport system in the economy of a nation cannot be overstated because of its links to other aspects of life. A good transportation system can be characterised by the availability of effective transport equipment and properly maintained transportation media in every part of the system [1]. Thus, it is imperative for every nation to have effective manufacturing systems that continually produce transport equipment. What's more, the importance of a country's transport equipment manufacturing does not end with moving citizens and goods around: it also serves as a way to boost the nation's economic power. It creates jobs and improves advances in technology, thereby contributing to the country's socio-economic development [2]. In order to achieve the effective manufacturing of transport equipment, a continuous improvement strategy is required to assess the performance of the production systems and their activities. In practice, an excellent way to assess the performance of manufacturing systems is to evaluate their sustainability. Assessing the sustainability of manufacturing activities has helped to solve the growing challenges associated with manufacturing practices globally. Thus it has become a good tool in assessing manufacturing activities and their processes [3].

Manufacturing transport equipment is a complex process because of the numerous activities that take place before the final product emerges. There are four major types of transport equipment: automotive (vehicles), locomotives (rail), ships, and aircraft. These four major groups can be further categorised into numerous types, depending on the need or application. The complex nature of these items of equipment requires virtually every manufacturing process to be used [4, 5]. Thus, improving the manufacturing of transport equipment requires that all necessary manufacturing processes be considered. A holistic approach

to the classification of manufacturing processes includes welding, casting, machining, fluid machinery (hydraulic and pneumatic applications), additive manufacturing, assembly technologies, autonomous technologies, and fourth industrial revolution processes. These processes can be further categorised into a number of other sub-classifications. These classifications continue to grow with applications and technologies in order to produce more and better products; and so it is necessary to assess their sustainability in manufacturing transport equipment [6]. As technology advances with research and development, manufacturing processes also improve by creating new methods and developing more advanced equipment. Manufacturing systems that produce transport equipment are not static: new designs with extended capabilities are required globally. That global need for new transportation equipment designs also gives rise to modern manufacturing processes, suggesting that existing systems need to be sustained and improved in order to meet the demand and gain a share of the competitive market.

A sustainable manufacturing system is usually achieved by considering all of the processes that the system requires, from the resources and materials applied in the production process, to the use of energy and its efficiency, the pollution produced by the technological practices, the acceptability of the new methods, their economic implications, the development of the employees working in the system, and much more. The factors to be considered in a sustainability assessment have been broadly divided into three indicators: environmental sustainability, economic sustainability, and social sustainability [7]. These are referred to as 'the traditional pillars'. Other indicators that are added in several sustainability assessments are specialised pillars that suit the features associated with the system under consideration [8]. Because it is usually not easy to evaluate the sustainability of manufacturing systems holistically, particularly for the production of complex products such as transport equipment, all the indicators of sustainability are usually analysed with an extended list of sub-indicators [9]. In relation to the environmental sustainability indicators, every issue that contributes to the total well-being of the environment as a result of the manufacturing processes needs to be considered. Similarly, metrics that contribute to the financial implications of the processes are usually considered under economic sustainability, while all the other issues that have to do with the activities and the continuous running of the system are usually categorised under social sustainability [10]. Several approaches have been applied to identify metrics for these indicators by identifying the interactions between the manufacturing processes [11].

In the literature, although there is no record of a generic method or of tools to evaluate the sustainability of manufacturing processes, especially given the indicators, there is an ongoing effort to assess the sustainability performance of manufacturing systems in respect of their processes [3, 12]. However, in recent times, several researchers have reported the use of multi-criteria decision-making (MCDM) models to assess sustainability performance [13]. MCDM models are generally classified as multi-attribute decision-making (MADM) or multi-objective decision-making (MODM) models [14]. In order to improve the computational integrity of MCDM models, sometimes they are fuzzified with membership functions or rough numbers in order to cater to the multi-dimensional nature of the decision criteria and to avoid any ambiguity that might arise from apportioning weights in the decision process [15, 16]. Recent researchers have described the application of MADM models in assessing the sustainability performance of manufacturing processes [17]. The application of these MADM models may be because of their excellent computational approaches to outranking alternatives and prioritising decision criteria. An example of such an MADM model is grey relational analysis, a powerful tool for comparing the performance of several alternatives by determining the values of their grades on the basis of their performance relative to an ideal solution [18, 19].

Several efforts have been made to apply MCDM to decision-making in manufacturing processes. The fuzzy AHP model has shown its relevance when the objective of the decision process is to identify an optimal choice that considers several decision criteria and sub-criteria. This is because of the comparative integrity of the fuzzy AHP model in respect of its fuzzified pairwise comparison matrices [20]. Examples of the application of fuzzy AHP in manufacturing decisions include the selection of a coal transportation mode from an open-pit mine to a thermic power plant [21], supplier selection problems [22, 23], and the multi-attribute comparison of catering service companies in Turkey [24]. The fuzzy event tree is a type of decision-making model that is applied to strategic decisions in manufacturing, such as supplier selection. It involves the use of AHP to determine the significance coefficient of the decision criteria, and then to build an event tree structure that takes into consideration all the decision criteria and computes the probabilities of each branch of the tree and level thresholds for the event tree state [25]. Further, the multi-dimensional nature of the decision criteria and the importance attached to the outcome of the decision process in manufacturing require that two or more decision-making models are hybridised in order to enhance the decision process and so obtain an optimal choice [20, 26]. Some applications of hybridised models in decision-making include the integration of fuzzy AHP and a fuzzy goal-programming model to

select the most suitable powered roof supports [27]; fuzzy AHP and multi-objective fuzzy goal programming for road header selection [28]; and AHP and a fuzzy weighted sum model to select transportation systems for open pit mines [29].

The assessment of the sustainability of manufacturing systems can be achieved by assessing the performance of the manufacturing processes involved in the system. This can best be achieved by considering the three pillars or sustainability indicators — environmental, economic, and social. As noted earlier, these processes include welding, casting, machining, fluid machinery, additive manufacturing, assembly technologies, autonomous technologies, and fourth industrial revolution processes. Also, the application of MCDM models is useful when assessing the sustainability performance of systems because of the models' computational intelligence in categorising decision problems into several criteria and sub-criteria; and that usually provides a rating of the performance of the alternatives. Thus this paper is based on the application of a fuzzy grey relational analysis as an MCDM tool to evaluate the sustainability performance of the manufacturing processes that are applied in the production of transport equipment, in order to identify the processes that need to be improved to achieve optimal performance.

2 METHODOLOGY

The method applied to assess the manufacturing processes in this article was based on fuzzy grey relational analysis (F-GRA). A framework of the methodology is presented in Figure 1. First, linguistic terms were established for the triangular fuzzy membership functions presented in Table I (Appendix A). Second, the sub-indicators for the environmental, economic, and social indicators were analysed, and fuzzified pairwise comparison matrices [30] were developed for the relative appearance of the sustainability indicators in the manufacturing processes and the application of the processes in transport equipment manufacturing (TEM), using experts' opinions (EOs). Fuzzy synthetic extent (FSE) values were determined from these matrices (equation 1) [31]. These values were harnessed to develop the sustainability matrices for the three indicators, taking into consideration the processes to manufacture transport equipment. The elements of these matrices were normalised by applying equation 2. The four steps of the F-GRA were applied, taking into consideration the three sustainability indicators, by using conventional mathematical models. These four steps included determining the reference series and distance matrix (equation 3), determining the fuzzy grey relational coefficients from the distance matrix (equation 4), and determining the fuzzy grey relational score using the relative appearance of the sustainability indicators in the manufacturing processes as weights (equation 5), which were normalised by applying equation 6 [32-34]. The fuzzified grades were defuzzified (equation 7) [35] in order to interpret the results.

$$\mathrm{FSE} = \sum_{j=1}^{v} \tilde{p}_{gi}^{j} \otimes \left[\sum_{i=1}^{u} \sum_{j=1}^{v} \tilde{p}_{gi}^{j} \right]^{-1} \tag{1}$$

$$\tilde{P}_N = \left[\frac{x_j - x_j^{\min}}{z_j^{\max} - x_j^{\min}}, \ \frac{y_j - x_j^{\min}}{z_j^{\max} - x_j^{\min}}, \ \frac{z_j - x_j^{\min}}{z_j^{\max} - x_j^{\min}} \right] \tag{2}$$

$$\tilde{P}_{ref} = [1 \ 1 \ 1]_1^j, \ [1 \ 1 \ 1]_2^j, \ [1 \ 1 \ 1]_3^j \ \ldots\ldots \ [1 \ 1 \ 1]_m^j \Big| ; j = 1, \ 2, \ 3 \ldots\ldots \ n$$
$$\tilde{P}_d = \left| \tilde{P}_{ref} - \tilde{P}_N \right| \tag{3}$$

$$\gamma \left[\tilde{P}_{ref}, \ \tilde{P}_N \right] = \frac{\Delta_{\min} + \xi \Delta_{\max}}{\Delta_{ij} + \xi \Delta_{\max}} \tag{4}$$

$$\Gamma \left[\tilde{P}_{ref}, \ \tilde{P}_N \right] = \sum_{j=1}^{j=m} \left[\tilde{W}_{ij}^N * \gamma \left[\tilde{P}_{ref}, \ \tilde{P}_N \right] \right]; \ s.t \ \sum_{j}^{m} \tilde{W}_{ij}^N = 1 \tag{5}$$

$$\tilde{W}_{ij}^N = \tilde{W}_{ij} \left[\sum_{j=1}^{j=m} \tilde{W}_{ij} \right]^{-1} \tag{6}$$

$$BNF\big|_p = \frac{x_{(p)} + 4y_{(p)} + z_{(p)}}{6} \tag{7}$$

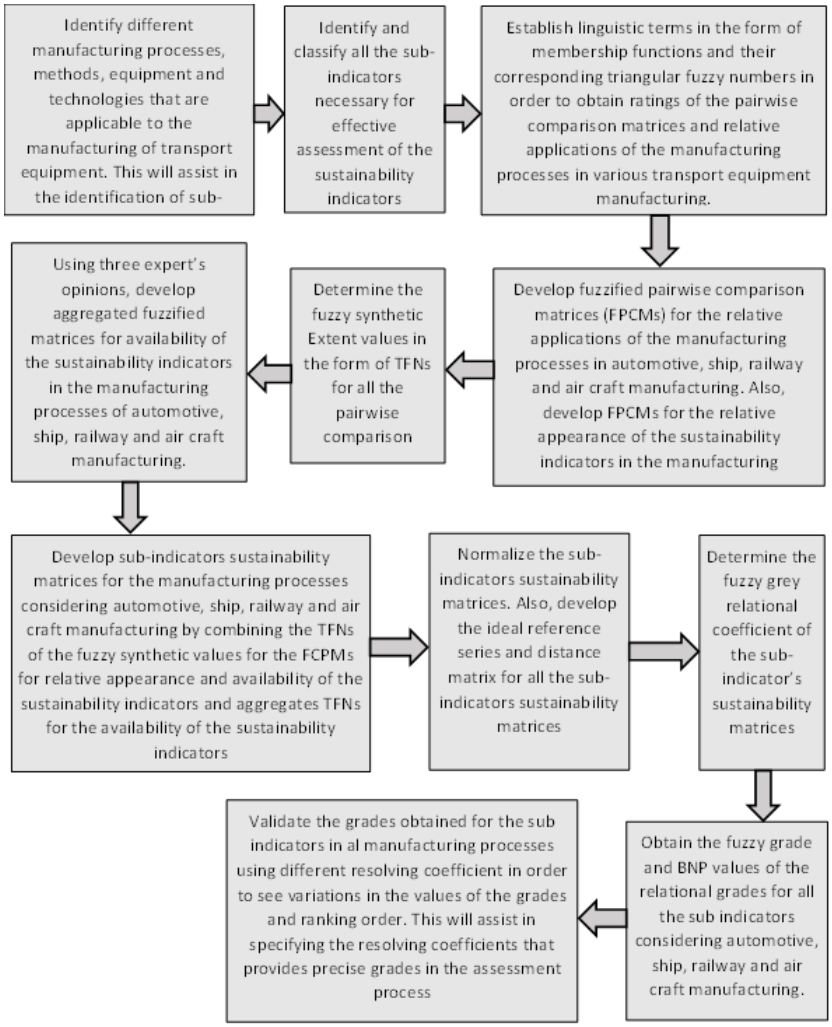

Figure 1: Framework of methodology applied in assessing the manufacturing processes

In equation 1, $\tilde{p}_{gi}^{j}$ is a triangular fuzzy number with membership function (x, y, z) representing the lower, modal, and upper functions respectively in a judgement matrix with *j* columns and *i* rows. This membership function can be defuzzified to obtain the best non-fuzzy (BNF) performance value, as shown in equation 7. $\tilde{P}_N$ is the normalised TFN in equation 2, with $x_j^{\min}$ and $z_j^{\max}$ representing the minimum and maximum lower and upper functions respectively in a column of the matrix. Also, $\tilde{P}_{ref}$ is the ideal series used to compare the normalised TFN ($\tilde{P}_N$) in order to obtain the distance matrix ($\tilde{P}_d$). In equation 4, $\gamma\left[\tilde{P}_{ref}, \tilde{P}_N\right]$ represents the grey relational coefficient, which is dependent on the distinguishing or resolving coefficient (ξ) and the minimum ($\Delta_{\min}$) and maximum ($\Delta_{\max}$) element in the distance matrix (Δ_{ij}). In equation 5, $\Gamma\left[\tilde{P}_{ref}, \tilde{P}_N\right]$ is the fuzzy relational score, which is a function of the normalised

weight ($\tilde{W}_{ij}^{N}$) obtained from the relative appearance of the sustainability indicators in the manufacturing processes.

3 APPLICATION OF THE MODEL

In order to simplify the analysis, consider the framework of the application process in Figure 2. Seven manufacturing processes (MPs) were considered, with four major TEM (automotive (ATM), ship (SPM), rail (RLM), and aircraft (ACM)) and the three sustainability indicators (SI) (environmental (EN), economic (EC), and social (SS)). Further, as presented in Appendix A (Tables II to XI), pairwise comparison matrices were developed for the relative application of MPs in different transport equipment manufacturing, the relative appearance of SIs in the MPs, and aggregating matrices for the availability of SIs in transport equipment manufacturing. The FSEs and aggregates obtained from these matrices were used to develop sustainability matrices for the EN, EC, and SS indicators, as shown in Tables I to III in Appendix B. These matrices were normalised in Tables IV to VI in Appendix B. By applying equation 3, the ideal reference and distance matrix for the EN indicator was obtained (as presented in Table 1); the ideal reference and distance matrices for EC and SS were also obtained, and are presented in Tables VII and VIII respectively in Appendix C. The fuzzy grey relational coefficients and grades were obtained from equations 4 and 5 respectively for the EN, EC, and SS indicators. Table 2 below presents the fuzzy grey relational coefficients and grades for the EN indicator; the fuzzy grey relational coefficients and grades for the EC and SS indicators are presented in Tables IX and X respectively in Appendix C. The best non-fuzzy (BNF) values of the grades were also obtained from equation 7, as shown in Tables 3 to 5 below. The environmental, economic, and social sustainability of the manufacturing processes in transport equipment manufacturing were obtained from these grades.

Table 1: Ideal reference series and distance matrix for EN sustainability of the MPs

	MP_1	MP_2	MP_3	MP_4	MP_5	MP_6	MP_7
	$\frac{12}{55}\ \frac{2}{9}\ \frac{5}{23}$	$\frac{17}{82}\ \frac{6}{29}\ \frac{11}{54}$	$\frac{14}{93}\ \frac{3}{20}\ \frac{5}{33}$	$\frac{14}{93}\ \frac{5}{32}\ \frac{3}{19}$	$\frac{87}{787}\ \frac{1}{9}\ \frac{49}{442}$	$\frac{6}{67}\ \frac{8}{91}\ \frac{1}{11}$	$\frac{5}{68}\ \frac{5}{74}\ \frac{4}{59}$
Ideal series	1 1 1	1 1 1	1 1 1	1 1 1	1 1 1	1 1 1	1 1 1
ATM	$\frac{906}{913}\ \frac{47}{59}\ \frac{4}{9}$	$\frac{58}{61}\ \frac{54}{71}\ \frac{9}{22}$	$1\ \frac{36}{49}\ \frac{3}{13}$	$\frac{50}{51}\ \frac{41}{51}\ \frac{13}{28}$	$\frac{7}{8}\ \frac{22}{39}\ 0$	$1\ \frac{58}{79}\ \frac{1}{4}$	$\frac{47}{52}\ \frac{44}{71}\ \frac{1}{16}$
SPM	$\frac{83}{95}\ \frac{5}{9}\ 0$	$\frac{16}{19}\ \frac{48}{89}\ 0$	$\frac{92}{99}\ \frac{18}{29}\ \frac{4}{83}$	$1\ \frac{36}{43}\ \frac{1}{2}$	$1\ \frac{83}{97}\ \frac{43}{74}$	$\frac{18}{17}\ \frac{28}{45}\ \frac{5}{91}$	$1\ \frac{68}{83}\ \frac{9}{19}$
RLM	$\frac{76}{77}\ \frac{3}{4}\ \frac{11}{38}$	$\frac{83}{85}\ \frac{21}{26}\ \frac{6}{13}$	$\frac{47}{50}\ \frac{47}{76}\ 0$	$1\ \frac{51}{61}\ \frac{19}{40}$	$\frac{29}{31}\ \frac{24}{35}\ \frac{19}{97}$	$\frac{64}{65}\ \frac{55}{84}\ \frac{1}{21}$	$\frac{34}{37}\ \frac{37}{61}\ 0$
ACM	$1\ \frac{47}{59}\ \frac{7}{17}$	$1\ \frac{80}{91}\ \frac{49}{78}$	$\frac{41}{42}\ \frac{63}{89}\ \frac{4}{23}$	$\frac{53}{60}\ \frac{27}{47}\ 0$	$\frac{85}{94}\ \frac{11}{34}\ \frac{5}{71}$	$\frac{22}{23}\ \frac{8}{13}\ 0$	$\frac{55}{59}\ \frac{37}{54}\ \frac{14}{79}$

Table 2: Fuzzified grey relational coefficient for EN sustainability of the MPs

	MP_1	MP_2	MP_3	MP_4	MP_5	MP_6	MP_7
	$\frac{12}{55}\ \frac{2}{9}\ \frac{5}{23}$	$\frac{17}{82}\ \frac{6}{29}\ \frac{11}{54}$	$\frac{14}{93}\ \frac{3}{20}\ \frac{5}{33}$	$\frac{14}{93}\ \frac{5}{32}\ \frac{3}{19}$	$\frac{87}{787}\ \frac{1}{9}\ \frac{49}{442}$	$\frac{6}{67}\ \frac{8}{91}\ \frac{1}{11}$	$\frac{5}{68}\ \frac{5}{74}\ \frac{4}{59}$
ATM	$\frac{1}{3}\ \frac{67}{84}\ \frac{81}{88}$	$\frac{43}{99}\ \frac{31}{38}\ \frac{37}{40}$	$\frac{1}{3}\ \frac{17}{19}\ \frac{81}{85}$	$\frac{20}{57}\ \frac{13}{16}\ \frac{57}{61}$	1 1 1	$\frac{1}{3}\ \frac{33}{37}\ \frac{73}{76}$	1 1 1
SPM	1 1 1	1 1 1	$\frac{31}{44}\ \frac{411}{412}\ 1$	$\frac{1}{3}\ \frac{34}{43}\ \frac{25}{27}$	$\frac{1}{3}\ \frac{17}{22}\ \frac{11}{12}$	$\frac{16}{23}\ \frac{141}{142}\ 1$	$\frac{1}{3}\ \frac{43}{52}\ \frac{73}{78}$
RLM	$\frac{10}{23}\ \frac{44}{53}\ \frac{12}{13}$	$\frac{32}{79}\ \frac{62}{79}\ \frac{10}{11}$	1 1 1	$\frac{19}{55}\ \frac{19}{24}\ \frac{83}{90}$	$\frac{46}{77}\ \frac{41}{46}\ \frac{68}{71}$	$\frac{66}{91}\ \frac{25}{26}\ \frac{33}{34}$	1 1 1
ACM	$\frac{33}{94}\ \frac{67}{84}\ \frac{87}{95}$	$\frac{1}{3}\ \frac{72}{97}\ \frac{17}{19}$	$\frac{2}{5}\ \frac{11}{12}\ \frac{61}{63}$	1 1 1	$\frac{33}{41}\ \frac{56}{59}\ \frac{93}{95}$	1 1 1	$\frac{4}{7}\ \frac{13}{14}\ \frac{49}{50}$

Table 3: Fuzzy and BNF values of relational grades for EN sustainability of the MPs

		MP_1	MP_2	MP_3	MP_4	MP_5	MP_6	MP_7
ATM	Fuzzy score	$\frac{4}{55}\ \frac{3}{17}\ \frac{1}{5}$	$\frac{1}{11}\ \frac{13}{77}\ \frac{13}{69}$	$\frac{1}{20}\ \frac{7}{52}\ \frac{13}{90}$	$\frac{1}{19}\ \frac{9}{71}\ \frac{4}{27}$	$\frac{1}{9}\ \frac{1}{9}\ \frac{1}{9}$	$\frac{2}{67}\ \frac{4}{51}\ \frac{2}{23}$	$\frac{5}{86}\ \frac{1}{15}\ \frac{4}{59}$
	BNF grade	$\frac{15}{92}$ 0.163	$\frac{7}{44}$ 0.159	$\frac{5}{41}$ 0.122	$\frac{2}{17}$ 0.118	$\frac{1}{9}$ 0.110	$\frac{1}{14}$ 0.072	$\frac{4}{61}$ 0.065
SPM	Fuzzy grade	$\frac{12}{55}\ \frac{2}{9}\ \frac{5}{23}$	$\frac{17}{82}\ \frac{6}{29}\ \frac{11}{54}$	$\frac{7}{66}\ \frac{3}{20}\ \frac{5}{33}$	$\frac{1}{20}\ \frac{7}{93}\ \frac{11}{75}$	$\frac{1}{27}\ \frac{4}{47}\ \frac{6}{59}$	$\frac{1}{16}\ \frac{2}{23}\ \frac{1}{11}$	$\frac{1}{41}\ \frac{1}{18}\ \frac{4}{63}$
	BNF grade	$\frac{11}{50}$ 0.220	$\frac{19}{92}$ 0.207	$\frac{1}{7}$ 0.143	$\frac{10}{87}$ 0.115	$\frac{2}{25}$ 0.080	$\frac{1}{12}$ 0.084	$\frac{4}{77}$ 0.052
RLM	Fuzzy grade	$\frac{9}{95}\ \frac{9}{49}\ \frac{1}{5}$	$\frac{1}{12}\ \frac{13}{80}\ \frac{5}{27}$	$\frac{1}{7}\ \frac{3}{20}\ \frac{14}{93}$	$\frac{4}{77}\ \frac{10}{81}\ \frac{13}{89}$	$\frac{6}{91}\ \frac{5}{51}\ \frac{7}{66}$	$\frac{5}{77}\ \frac{6}{71}\ \frac{5}{57}$	$\frac{5}{68}\ \frac{5}{74}\ \frac{1}{15}$
	BNF grade	$\frac{17}{99}$ 0.172	$\frac{2}{13}$ 0.153	$\frac{3}{20}$ 0.150	$\frac{3}{26}$ 0.115	$\frac{18}{85}$ 0.094	$\frac{4}{49}$ 0.082	$\frac{5}{73}$ 0.068
ACM	Fuzzy grade	$\frac{1}{13}\ \frac{3}{17}\ \frac{1}{5}$	$\frac{2}{29}\ \frac{2}{13}\ \frac{2}{11}$	$\frac{3}{50}\ \frac{4}{29}\ \frac{11}{75}$	$\frac{14}{93}\ \frac{5}{32}\ \frac{3}{19}$	$\frac{4}{45}\ \frac{7}{67}\ \frac{5}{46}$	$\frac{28}{313}\ \frac{8}{91}\ \frac{6}{67}$	$\frac{1}{24}\ \frac{1}{16}\ \frac{1}{15}$
	BNF grade	$\frac{9}{55}$ 0.164	$\frac{14}{97}$ 0.144	$\frac{12}{95}$ 0.126	$\frac{7}{45}$ 0.155	$\frac{4}{39}$ 0.103	$\frac{3}{34}$ 0.088	$\frac{3}{50}$ 0.060

Table 4: Fuzzy and BNF values of relational grades for EC sustainability of the MPs

		MP_1	MP_2	MP_3	MP_4	MP_5	MP_6	MP_7
ATM	Fuzzy grade	$\frac{2}{61}\ \frac{7}{94}\ \frac{2}{23}$	$\frac{1}{20}\ \frac{2}{21}\ \frac{4}{37}$	$\frac{2}{33}\ \frac{16}{97}\ \frac{10}{57}$	$\frac{1}{29}\ \frac{1}{13}\ \frac{1}{11}$	$\frac{3}{19}\ \frac{9}{58}\ \frac{2}{13}$	$\frac{2}{35}\ \frac{15}{98}\ \frac{8}{47}$	$\frac{13}{99}\ \frac{12}{71}\ \frac{6}{35}$
	BNF grade	$\frac{3}{43}$ 0.070	$\frac{8}{89}$ 0.090	$\frac{10}{67}$ 0.149	$\frac{6}{83}$ 0.072	$\frac{9}{58}$ 0.155	$\frac{7}{50}$ 0.140	$\frac{8}{49}$ 0.163
SPM	Fuzzy grade	$\frac{5}{51}\ \frac{8}{85}\ \frac{9}{95}$	$\frac{10}{83}\ \frac{60}{509}\ \frac{2}{17}$	$\frac{4}{29}\ \frac{8}{43}\ \frac{5}{27}$	$\frac{1}{30}\ \frac{4}{53}\ \frac{1}{11}$	$\frac{1}{19}\ \frac{3}{25}\ \frac{10}{71}$	$\frac{1}{10}\ \frac{15}{88}\ \frac{8}{45}$	$\frac{2}{35}\ \frac{1}{7}\ \frac{14}{87}$
	BNF grade	$\frac{2}{21}$ 0.095	$\frac{11}{93}$ 0.118	$\frac{8}{45}$ 0.178	$\frac{1}{14}$ 0.071	$\frac{10}{89}$ 0.112	$\frac{4}{25}$ 0.160	$\frac{8}{61}$ 0.131
RLM	Fuzzy grade	$\frac{2}{47}\ \frac{7}{90}\ \frac{3}{23}$	$\frac{1}{21}\ \frac{9}{98}\ \frac{5}{47}$	$\frac{2}{11}\ \frac{5}{27}\ \frac{11}{60}$	$\frac{1}{29}\ \frac{7}{93}\ \frac{1}{11}$	$\frac{2}{21}\ \frac{9}{65}\ \frac{5}{34}$	$\frac{1}{10}\ \frac{13}{79}\ \frac{5}{29}$	$\frac{7}{41}\ \frac{16}{93}\ \frac{8}{47}$
	BNF grade	$\frac{5}{68}$ 0.073	$\frac{2}{23}$ 0.087	$\frac{7}{38}$ 0.184	$\frac{1}{14}$ 0.071	$\frac{13}{98}$ 0.133	$\frac{11}{71}$ 0.155	$\frac{6}{35}$ 0.172
ACM	Fuzzy grade	$\frac{1}{27}\ \frac{1}{13}\ \frac{7}{80}$	$\frac{1}{25}\ \frac{8}{91}\ \frac{2}{19}$	$\frac{6}{65}\ \frac{10}{57}\ \frac{2}{11}$	$\frac{93}{928}\ \frac{3}{31}\ \frac{1}{10}$	$\frac{14}{89}\ \frac{2}{13}\ \frac{11}{72}$	$\frac{7}{41}\ \frac{8}{45}\ \frac{5}{28}$	$\frac{7}{62}\ \frac{14}{85}\ \frac{13}{76}$
	BNF grade	$\frac{1}{14}$ 0.072	$\frac{1}{12}$ 0.083	$\frac{7}{43}$ 0.163	$\frac{5}{51}$ 0.098	$\frac{2}{13}$ 0.154	$\frac{3}{17}$ 0.177	$\frac{11}{70}$ 0.157

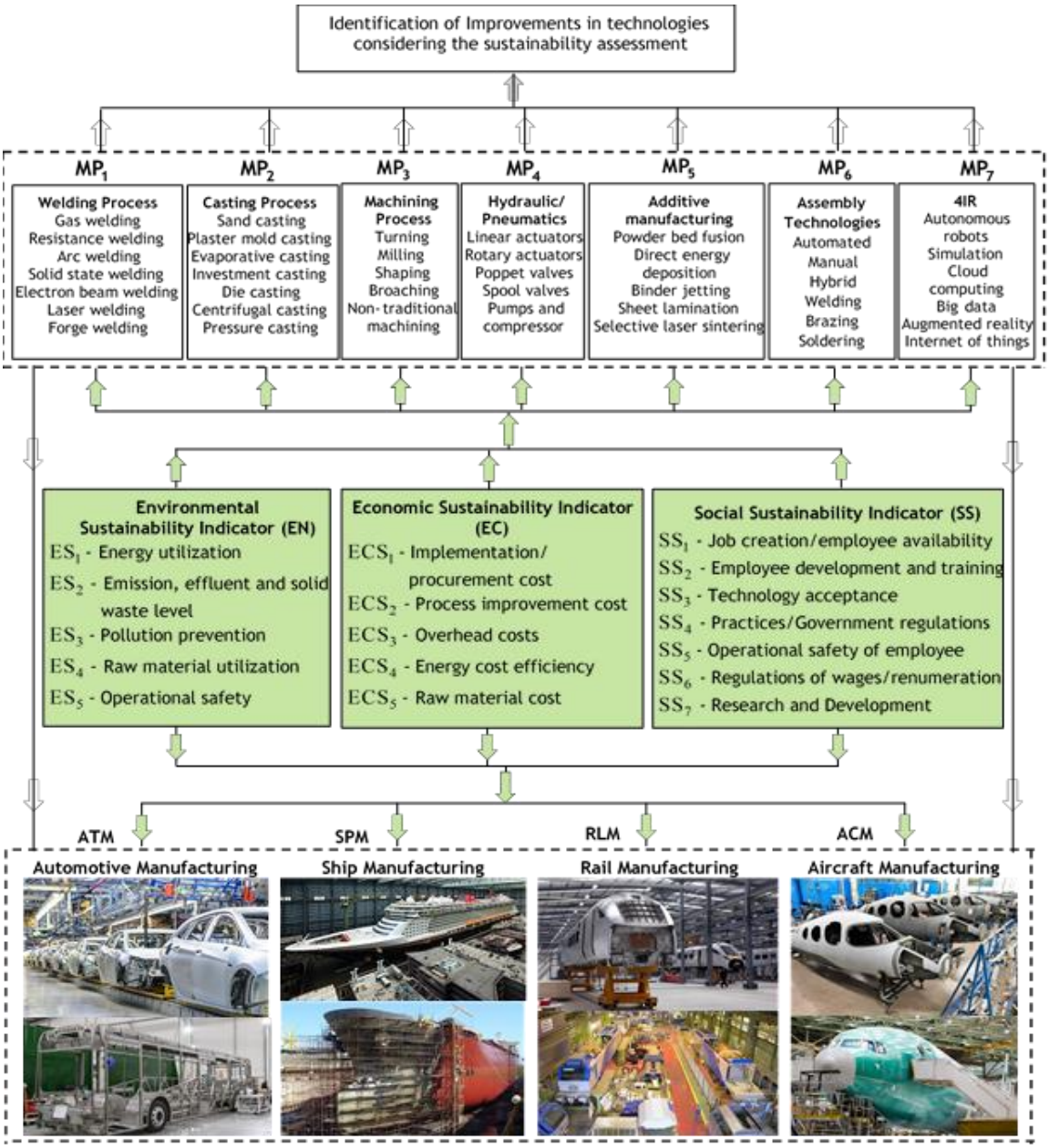

Figure 2: Assessing sustainability of MPs in transport equipment manufacturing

Table 5: Fuzzy and BNF values of relational grades for SS sustainability of the MPs

		MP_1	MP_2	MP_3	MP_4	MP_5	MP_6	MP_7
ATM	Fuzzy grade	$\frac{3}{61}\ \frac{12}{97}\ \frac{3}{22}$	$\frac{3}{38}\ \frac{1}{7}\ \frac{7}{44}$	$\frac{1}{22}\ \frac{9}{70}\ \frac{8}{59}$	$\frac{4}{79}\ \frac{1}{9}\ \frac{3}{23}$	$\frac{3}{29}\ \frac{1}{10}\ \frac{4}{39}$	$\frac{5}{82}\ \frac{13}{80}\ \frac{6}{35}$	$\frac{5}{37}\ \frac{8}{59}\ \frac{9}{67}$
	BNF grade	$\frac{5}{44}$ 0.113	$\frac{13}{96}$ 0.135	$\frac{8}{69}$ 0.116	$\frac{3}{29}$ 0.104	$\frac{10}{99}$ 0.101	$\frac{5}{34}$ 0.147	$\frac{5}{37}$ 0.135
SPM	Fuzzy grade	$\frac{13}{88}\ \frac{7}{48}\ \frac{1}{7}$	$\frac{15}{92}\ \frac{129}{778}\ \frac{1}{6}$	$\frac{1}{19}\ \frac{13}{99}\ \frac{10}{73}$	$\frac{1}{23}\ \frac{10}{97}\ \frac{12}{95}$	$\frac{1}{29}\ \frac{5}{67}\ \frac{9}{98}$	$\frac{2}{29}\ \frac{13}{79}\ \frac{13}{76}$	$\frac{1}{22}\ \frac{8}{75}\ \frac{5}{41}$
	BNF grade	$\frac{7}{48}$ 0.146	$\frac{1}{6}$ 0.165	$\frac{5}{42}$ 0.119	$\frac{3}{31}$ 0.097	$\frac{1}{14}$ 0.071	$\frac{3}{20}$ 0.150	$\frac{9}{91}$ 0.099
RLM	Fuzzy grade	$\frac{6}{95}\ \frac{1}{8}\ \frac{5}{37}$	$\frac{1}{15}\ \frac{2}{15}\ \frac{2}{13}$	$\frac{7}{51}\ \frac{13}{94}\ \frac{5}{36}$	$\frac{4}{85}\ \frac{2}{19}\ \frac{7}{55}$	$\frac{3}{52}\ \frac{5}{58}\ \frac{3}{31}$	$\frac{3}{31}\ \frac{1}{6}\ \frac{9}{53}$	$\frac{8}{63}\ \frac{11}{84}\ \frac{3}{23}$
	BNF grade	$\frac{7}{60}$ 0.117	$\frac{1}{8}$ 0.126	$\frac{13}{94}$ 0.138	$\frac{1}{10}$ 0.099	$\frac{1}{12}$ 0.083	$\frac{5}{32}$ 0.156	$\frac{3}{23}$ 0.130
ACM	Fuzzy grade	$\frac{2}{39}\ \frac{6}{49}\ \frac{5}{37}$	$\frac{5}{92}\ \frac{3}{23}\ \frac{7}{51}$	$\frac{5}{93}\ \frac{3}{23}\ \frac{7}{51}$	$\frac{3}{23}\ \frac{9}{67}\ \frac{5}{36}$	$\frac{7}{87}\ \frac{3}{32}\ \frac{1}{10}$	$\frac{15}{82}\ \frac{9}{50}\ \frac{10}{57}$	$\frac{7}{80}\ \frac{1}{8}\ \frac{3}{23}$
	BNF grade	$\frac{8}{71}$ 0.113	$\frac{5}{42}$ 0.119	$\frac{7}{59}$ 0.119	$\frac{9}{67}$ 0.134	$\frac{5}{54}$ 0.092	$\frac{16}{89}$ 0.180	$\frac{3}{25}$ 0.120

4 DISCUSSION AND VALIDATION

The results obtained from the application of the fuzzified grey relational analysis to the assessment of the manufacturing processes in transport equipment manufacturing show that it is viable for assessing manufacturing processes. The increase in the grades of the welding and casting machining processes under environmental sustainability (Figure 3) signifies that more environmental improvement needs to be considered in these processes, given the needs in transport equipment manufacturing. Improvements to environmental practice could be achieved by improving the environmental grades of additive manufacturing, assembly technologies, and autonomous processes, as their values were low under environmental sustainability. Conversely, as shown in Figure 4, the financial implications of machining, additive manufacturing, assembly technologies, and autonomous processes should be controlled because of their increased grades under economic sustainability. Also, the social indicator of additive manufacturing needs to be improved, given its low grade (Figure 5). It is worth noting that the improvement of these processes could be achieved by analysing the sub-indicators or metrics of the sustainability indicators.

In order to validate the consistency and rationality of the computational process, a sensitivity analysis was carried out by adding the grades of the manufacturing process in each type of transport equipment manufacturing. The values obtained from this addition were expected to be constant for every value of the resolving coefficient, within the range 0.1 to 1.0. The fuzzy grey relational matrices and grades were computed for each manufacturing process, and were added to other processes under the same equipment manufacturing, given the three sustainability indicators. The accumulated grades were defuzzified to obtain different grades for the manufacturing of transport equipment.

The computational process provided different grades for the manufacturing of transport equipment, given the sustainability indicators and the range of values of the resolving coefficient [$\xi = 0.1$ to $\xi = 1.0$]. The ranges of different resolving coefficients are shown in Table 6. It is evident that the rankings differ under each sustainability indicator for the accumulated manufacturing process values. For environmental and economic sustainability, the value of the accumulated manufacturing process grades falls in the same ranking order for all values of the resolving coefficients. However, there is a variation in the ranking order of the values of the accumulated manufacturing process grades in the social sustainability assessment from resolving the coefficients range [$\xi = 0.1$ to $\xi = 0.3$] and from [$\xi = 0.5$ to $\xi = 1.0$], while a tie appeared at [$\xi = 0.4$], as shown in Figure 6. Thus it is advisable to keep the resolving coefficient within the range of 0.5 to 1.0. Given the result of the sensitivity analysis, it can be hypothetically stated that the computational

process is viable in respect of stability and uniformity over a wide range of the resolving coefficient [$\xi = 0.5$ to $\xi = 1.0$].

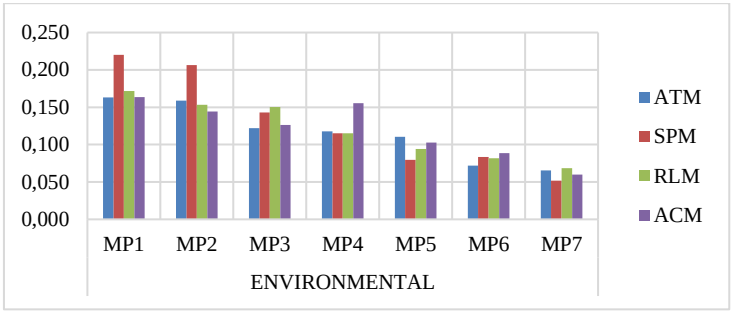

Figure 3: Environmental sustainability of MPs in TEM

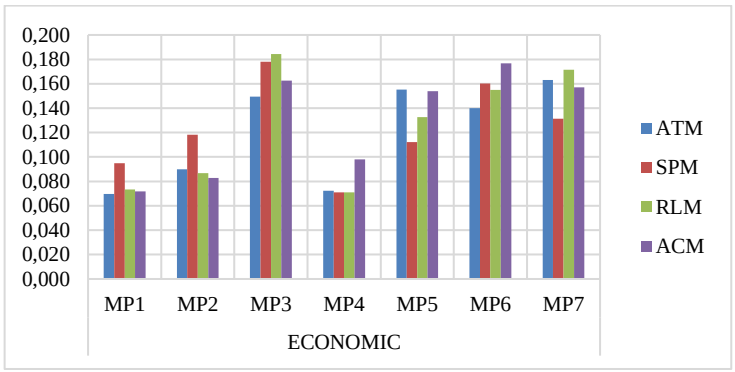

Figure 4: Economic sustainability of MPs in TEM

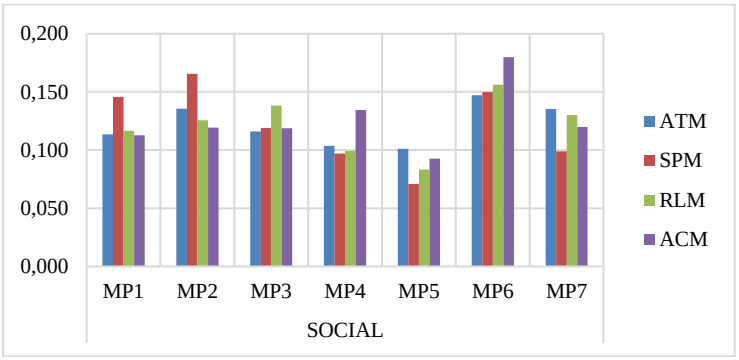

Figure 5: Social Sustainability of MPs in TEM

Table 6: Sensitivity analysis to validate the assessment model

Sustainability indicators	Accumulated grades for manufacturing process for each type of transport equipment	Ranges of resolving coefficients (RCs)									
		$\xi = 0.1$	$\xi = 0.2$	$\xi = 0.3$	$\xi = 0.4$	$\xi = 0.5$	$\xi = 0.6$	$\xi = 0.7$	$\xi = 0.8$	$\xi = 0.9$	$\xi = 1.0$
Environmental (ENV)	ATM	0.731	0.757	0.778	0.795	0.809	0.822	0.833	0.843	0.852	0.859
	SPM	0.852	0.869	0.882	0.892	0.900	0.907	0.913	0.918	0.923	0.927
	RLM	0.758	0.784	0.804	0.821	0.835	0.847	0.857	0.866	0.874	0.881
	ACM	0.772	0.795	0.813	0.828	0.841	0.851	0.861	0.869	0.876	0.883
Economic (ENC)	ATM	0.770	0.794	0.812	0.827	0.839	0.850	0.860	0.868	0.875	0.882
	SPM	0.802	0.824	0.841	0.855	0.866	0.875	0.883	0.890	0.897	0.902
	RLM	0.813	0.834	0.850	0.864	0.875	0.884	0.892	0.899	0.905	0.910
	ACM	0.853	0.870	0.884	0.894	0.903	0.910	0.916	0.922	0.926	0.930
Social (SOC)	ATM	0.791	0.811	0.827	0.840	0.852	0.862	0.871	0.878	0.885	0.891
	SPM	0.789	0.807	0.822	0.836	0.847	0.857	0.865	0.873	0.880	0.886
	RLM	0.775	0.801	0.820	0.836	0.849	0.860	0.870	0.878	0.885	0.892
	ACM	0.819	0.839	0.854	0.867	0.877	0.886	0.893	0.900	0.906	0.911

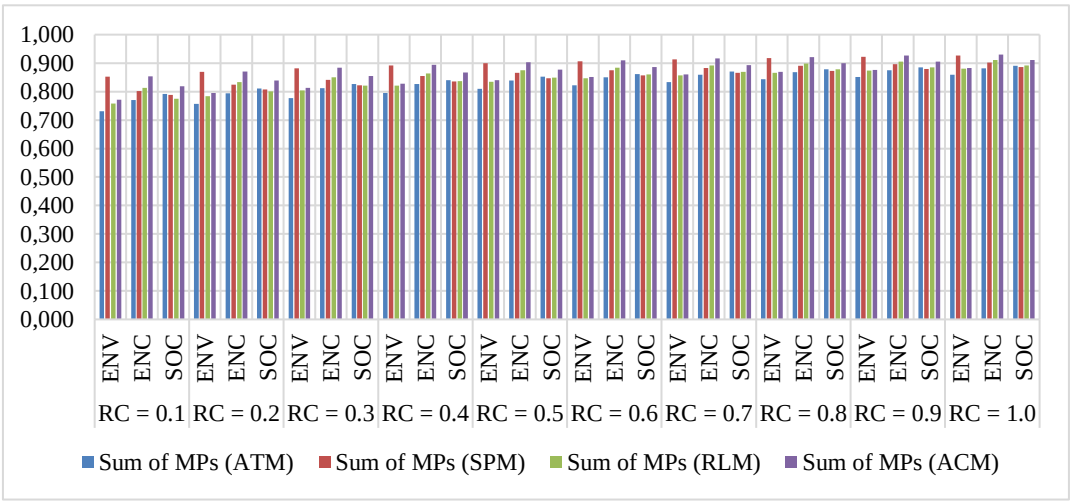

Figure 6: Graphical representation of accumulated grades of SIs for sensitivity analysis

5 CONCLUSION

The importance of transportation and of the manufacture of transport equipment in a national economy cannot be overemphasised because of their contributions to socio-economic and technical growth. In order to have a sustainable manufacturing system for the production of transport equipment, it is necessary to assess the manufacturing processes. This paper has been able to evaluate the performance of several manufacturing processes in the manufacturing system of transport equipment, based on fuzzified grey relational analysis, and has identified processes that need to be improved. The results obtained from this study have also identified some key indicators that need to be improved on by practitioners in the field of transport equipment manufacturing. For instance, a consideration of environmental sustainability is needed in manufacturing processes such as welding, casting, and machining. Consideration also needs to be given to the financial requirements of carrying out manufacturing processes such as machining, additive manufacturing, and automation, given their high grades for economic sustainability. The low grade for additive manufacturing under social sustainability implies that the technical know-how of the process is yet to be understood in the system. In view of this, practitioners could organise training sessions on the additive manufacturing process, and technical colleges and universities of technology could also improve their course content in respect of the additive manufacturing process. However, future work is still possible on deriving the elements of the judgement matrices from the quantitative and qualitative performance of

these processes, rather than from the expert opinions used in the present study. Also, to reduce the computational volume, the fuzzified pairwise comparison matrices could be automated in decision tools such as the SuperDecisions application software for the analytic hierarchy process.

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