

Design and planning of decentralized production networks under high product variety demand

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Abstract

In today's era of customer-driven markets, manufacturers throughout the globe realize that the efficient collaboration with their supply chain partners is amongst the most crucial factors for improved profits. The necessity to effectively coordinate the activities of the independent partners, and to align their objectives towards a common goal, is evident. This research work, presents a methodology for the identification of efficient production and transportation schemes, in decentralized and centralised manufacturing environments. The methodology allows the generation of feasible alternative production and transportation schemes, using exhaustive search and intelligent algorithm methods. The schemes are simulated and evaluated against multiple user-defined criteria such as cost, time, environmental impact and quality. The most efficient alternatives are visualised, and can be used for the planning and coordination of geographically dispersed facilities, that carry out the production of highly customized products. The proposed approach is implemented through a tool, and applied on a case study from the automotive sector.

Keywords:

Planning, Decision Making, Customisation

1 INTRODUCTION AND MOTIVATION

The globalisation trend of the last decades imposes new requirements to the Original Equipment Manufacturers (OEMs). The short life-cycles, short time-to-market and the increased outsourcing activities, create additional burdens. Moreover, the manufacturing at dispersed facilities and the increasing demand for high product variety, increases the complexity of production [1]. Now, more than ever, OEMs need to optimise their manufacturing and transportation activities in a cost-effective, timely and eco-friendly manner [2]. The continuously increasing customer demands towards higher product variety and uniqueness further increases the turbulences [3]. Towards trying to compete, industries throughout the world have increased their outsourcing activities, aiming at reduced costs and times [4]. The traditional structure of a stand-alone company connecting to the market and to suppliers only via delivery and procurement of products, is nowadays invalid. Efficient cooperation between enterprises is utterly important [5]. Adding to that, the globalisation of manufacturing activities entails increased transportation distances and high quality standards. These factors create further disturbances in the operation of manufacturing systems. Moreover, strict environmental regulations comprise an additional constraint to the manufacturers. An example is the obligation to comply with the directives that emerge from the Kyoto Protocol [6]. The demand for goods has been increased and so has the demand for natural resources and energy [7]. However, since resources and energy are finite, new ways of producing more with less ought to be found [8]. Centralisation has been replaced by decentralisation and top-down analytic methods by bottom-up synthesis [9]. The decentralisation of production comes with an increase of the required processes, both direct and indirect. Results revealed that the location of suppliers is a significant factor that can alter the raw material's embodied energy. Different locations use electricity generated from various combinations of energy sources [10]. The careful selection of suppliers combined with the reduction of transportation routes and distances

can significantly reduce the environmental impact. In addition, it can reduce the required cost and time for the production of customised products. The aim of the presented research work is to identify efficient network configurations in a cost-effective, quick and eco-friendly manner. Real-life industrial data have been used for the validation of the methodology. The results that derive are presented and discussed.

1.1 State of the Art

The transportation costs for the main intercontinental transport modes, air and sea, keeps dropping considerably. This allows easier distribution of raw materials and components to dispersed production plants, at locations with low human labour costs. It also enables the export of finished goods to foreign markets [11]. Mass Customisation appeared in the 80's in response to consumer demands for higher product variety [12]. OEMs started to increase the available variants of their standard product. They provided optional features and allowed the customers to select them on demand. Mass customisation focuses on implementing an Economy of Scope through market segmentation. This can be achieved by procuring product variants and options, based on common product architectures. Afterwards, the customers are allowed to select unique design combinations [13]. The high product variety can be cost-effectively achieved through a series of alternative product options. The customers are able to select the assembly combination that they prefer the most. Thus, economy of scale is achieved at the component level. Reconfigurable assembly systems are utilised in order to create high variety for the economy of scope of the final assembly [14]. The current trend indicates that customers require unique products of high quality, which are also available at low prices and at the right time [15]. Enterprises have to respect not only their own benefits and interests, but also their customers' and cooperating stakeholders', including the social and natural environments [16].

In addition, the environmental consciousness is nowadays raised. The forecasts for future energy consumption indi-

cate a deceleration of 1.6% at the growth of primary energy consumption up to 2030. The previous 20 years this indicator decelerated at 2.0% p.a. Moreover, the energy consumption per capita grows at 0.7% p.a.; approximately the same rate as it has been since 1970. The transportation and manufacturing sectors lead the growth of final energy consumption, especially in rapidly developing economies. The 2030 projection indicates that the industrial sector will account for 60% of the projected growth of energy demand [17].

The manufacturing sector is a key driving force of the European economy. In 2010 34 million people were employed in the EU-27 manufacturing sector, representing 15.9% of the total employment [18]. Indirectly (with all related sectors and activities), manufacturing accounts for close to 50% of the European economy. The automotive sector comprises a significant part of the EU manufacturing activities. Europe is the world's largest vehicle producer with an output of over 15 million passenger cars, vans, trucks and buses per year. This comprises the 25% of worldwide vehicle production. The automotive industry accounts for 2.3 million direct jobs and another 10.4 million in directly related manufacturing and other sectors [19]. Thereby, special focus needs to be given to the European automotive industry. A survey conducted in the U.K. related to automotive products, revealed that 61% of the customers wanted their vehicle to be delivered within 14 days [20][21]. The automotive industry is an indicative example of mass producing systems that is currently trying to cope with the mass customisation needs. The manufacturing activities in the currently turbulent environment are in great part characterised by uncertainty. However, the majority of the existing planning approaches assume that information and environment are deterministic factors [22]. They consider the strategic impact of mass customization without addressing to specific implementation issues [23]. In order to survive in the current landscape, high performance is required in dimensions of cost, quality, speed, environmental friendliness, and adaptability to demand variations [24].

2 NETWORK CONFIGURATION AND PRODUCT MODELLING

2.1 Centralised and Decentralised Network Configurations

The supply chain of the presented pilot case comprises of 30 partners, coming from a European Automotive manufacturer. The partners are OEMs, Suppliers and Dealers that cooperate in order to carry out customer orders. Different actors are capable of different operations at varied cost, time, quality and environmental impact. The centralized supply chain is modelled in such a way that assembly tasks can be performed only by the OEM at one of the owned plants. After the final hood assembly is performed, the OEM delivers the product to the sales representatives (dealers), so that it can be sold to a customer. In a decentralised scenario however, the assembly of the hood and the customisation activities can be carried out by suppliers or even dealers. The decentralized network modelling, allows final assembly operations or special works (e.g. application of the warp cast carbon) to be performed at a dealer or a supplier site, close to the customer. The differences in the two network configurations are depicted in the figure below by the red arrows (Figure 1). The OEMs can directly deliver a product to a customer. In some cases, a supplier can perform the final assembly and deliver the product to a nearby customer. This can enable, under circumstances, the efficient implementation of mass customisation as described in [25].

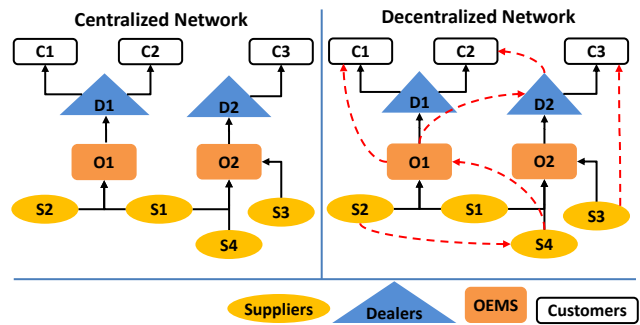


Figure 1: Models of centralized and decentralized production networks.

2.2 Product Structure and Bill of Processes

The customised product under investigation is a car hood that is produced in four variants. The car hood comprises 6 components, two of which are optional customisation additions. The customisable components are offered by the OEM to the customers. The basic components of the hood are the external hood cover, the hood frame, the hinge support and the lock support. The customisation options include an ornament and a wrap cast carbon. These components are either manufactured internally at the OEM, or they are outsourced to Suppliers (Figure 2).

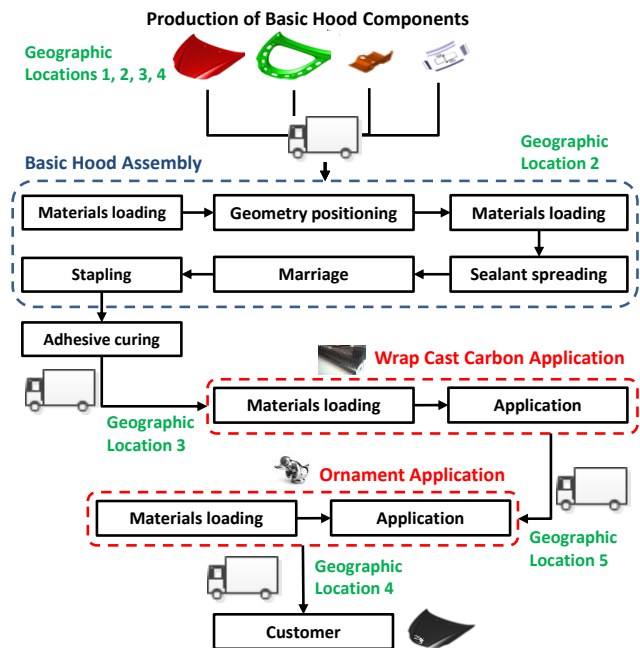


Figure 2: Bill of Processes for the fully customised hood, for a decentralised manufacturing scenario.

The variants of the car hood that were used in the experiments have different degrees of customisation as follow:

- L1 (Basic Hood):** This variant is a non-customised product, comprising four components, namely the external cover, the hood frame, the hinge support and the lock support.
- L2a (Ornament):** This variant is customised by the customers and comprises the basic hood assembly and the ornament option.
- L2b (Wrap Cast Carbon):** This variant is customised by the customers and comprises the basic hood assembly and the wrap cast carbon option.
- L3 (Ornament + Wrap Cast Carbon):** This variant is fully customised, comprising the basic hood assembly, the wrap cast carbon, and ornament options.

L4 (Two Ornaments + Wrap Cast Carbon): This variant is basically the L3 with an additional Ornament selected by the customer.

3 DESIGN AND PLANNING METHOD

The decision making procedure in the presented case study includes resource-task assignment decisions. The resources and tasks can be considered simultaneously. Each task can be assigned to a specific resource, in contrast to dispatch rules, which only select the next task to be performed. Moreover, the decision-making procedure considers multiple criteria simultaneously. The four steps of the decision making process can be summed up to the following [26]:

- 1 Form a set of alternatives
- 2 Determine a set of decision-making criteria
- 3 Calculate the Utility Value of each alternative with respect to the selected criteria, and
- 4 Select the Best Alternative.

The decision making process can be formalised in a decision matrix (Figure 3). The rows in a decision matrix represent the alternatives (ALT₁, ALT₂, ALT₃,..., ALT_m) and the columns represent the criteria (CR₁, CR₂, CR₃,..., CR_n). The cells of the matrix represent the normalised value of the criteria for the specific alternative. The column "Utility" represents the calculated utility value for each criterion (U₁, U₂, U₃,..., U_m).

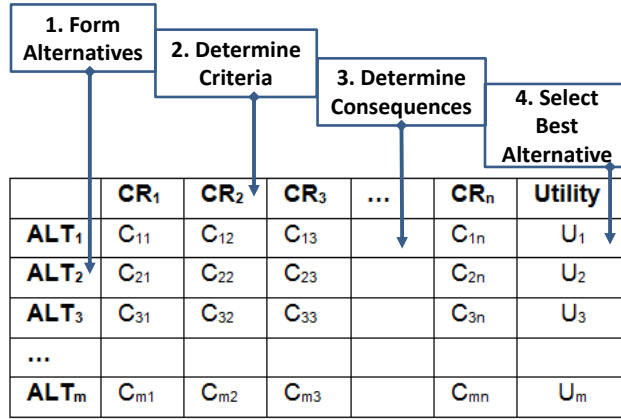


Figure 3: The Decision Matrix.

3.1 Intelligent Search Algorithm

The intelligent algorithm for the evaluation and selection of the manufacturing scheme alternatives is described in [31]. An example of the intelligent search algorithm is presented in Figure 4.

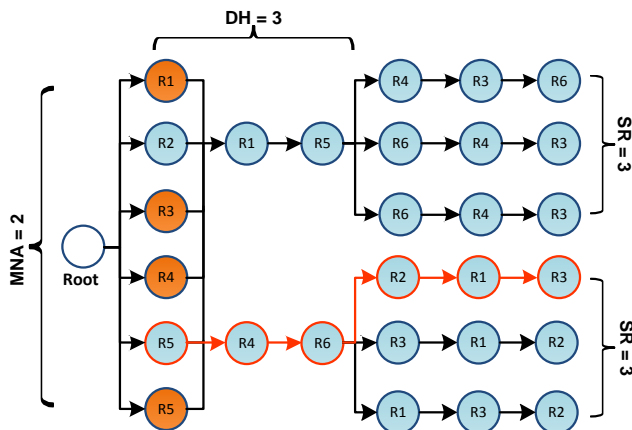


Figure 4: Intelligent search algorithm example.

The intelligent search algorithm uses three adjustable control parameters. The Maximum Number of Alternatives (MNA) controls the breadth of the search, and the Decision Horizon (DH) controls the depth. The Sampling Rate (SR), guides the search through the solution space. The nodes R1, R2,..., R5, represent decision points where a task is assigned to a resource. The red highlighted path represents an alternative production scheme (Figure 4).

The intelligent algorithm is described in pseudo-code form below [25][30]:

```

Step 1: Starting at the Root
FOR all DH Layers UNTIL MNA is reached
  Create random Assignments (Alternatives)
Step 2: FOR each Branch/Alternative
  UNTIL SR is reached
    Generate SR random Samples (alternatives)
Step 3: FOR each Sample
    Calculate the Criteria Scores
Step 4: Calculate the score of the
  Branch as the average score achieved
  by its Samples
Step 5: Calculate the Utility Value of
  each Alternative
Step 6: Select the Alternative with
  the highest Utility Value
Step 7: Store the Assignments of the
  selected Alternatives
  END FOR
END FOR
END FOR

```

3.2 Exhaustive Search

During the exhaustive search method, all the manufacturing and transportation alternatives are generated and evaluated. The exhaustive search algorithms guarantee that the best alternative is found with respect to the selected criteria. However, significant computational effort and time are required.

3.3 Criteria

The quality of the production and transportation schemes is quantified by the means of the following criteria:

- 1 Cost (C): The cost is calculated as the sum of the production cost and the transportation cost [25]:

$$C = \sum_{k=1}^K P c_k + \sum_{r=1}^R T r_{Cr} \quad (1)$$

where:

- P c_k: production cost for the task k (k ∈ N/k = 1, 2, ..., K) (€),
- T r_{Cr}: transportation cost for the root r (r ∈ N/r = 1, 2, ..., R) (€).

- 2 Lead time (L): The lead time is calculated from the point that an order is placed to the point that it is actually available for satisfying customer demand [25][27]:

$$L = \sum_{k=1}^K P t_k + \sum_{r=1}^R T t_r + \sum_{k=1}^K S t_k \quad (2)$$

where:

- P t_k: production time for the task k,
- T t_r: transportation time for the root r,
- S t_k: setup time for the task k.

- 3 Energy Consumption (EC): This indicator takes into consideration the Watt specifications and processing time of each resource [28]:

$$EC = EC_T + EC_P = \sum_{r=1}^R D_r * TC + \sum_{k=1}^K P t_k * RW_k \quad (3)$$

where:

- EC: the sum of Energy Consumption for the manufacturing scheme (Joule),
 - EC_T : the sum of the Energy Consumption due to transportation activities (Joule),
 - D_r : transportation distance covered for the root r (Km),
 - TC: Energy Consumption per kilometre (J/km) [29],
 - EC_P : the sum of the Energy Consumption of all the processes (J),
 - RW_k : the Watts of the resource responsible for the task k (J/s).
- 4 CO₂ Emissions (CO): The CO₂ Emissions value is calculated by the distance travelled and the emission of CO₂ per kilometre (km) [25][28]:

$$CE = \sum_{r=1}^R \frac{G * D_r}{N} \quad (4)$$

where:

- G: CO₂ emissions/Km [29],
 - N: number of products that one truck is carrying
- 5 Quality: The quality indicator is calculated based on the mean quality of the parts, services that the supply chain partner provides and on their respect of due dates. The quality takes values in the range of [0-100].

$$QL = \frac{\sum_{k=1}^K QL_k}{K} \quad (5)$$

where:

- QL_k : the quality of the supplier that performs the task k.

Normalisation of Criteria Values

The assessment of the manufacturing and transportation alternative schemes requires the consideration of multiple criteria, which may be conflicting. As an example, we examine the Cost and Quality indicators. Low cost production tends to produce goods of lower quality. Therefore, in order for the alternatives to be compared, based on the values of the criteria, a normalisation of the values is required. The normalisation is carried out for benefit criteria (6) (Quality) that should be maximised and for cost criteria (7) (Production Cost, Lead Time, CO₂ Emissions, Energy Consumption) that should be minimised [30][32].

$$\hat{C}_{ij} = \frac{C_{ij} - C_j^{min}}{C_j^{max} - C_j^{min}} \quad (6)$$

$$\hat{C}_{ij} = \frac{C_j^{max} - C_{ij}}{C_j^{max} - C_j^{min}} \quad (7)$$

where:

- C_{ij} is the consequence value of alternative i with respect to criterion j, and
- \hat{C}_{ij} is the normalised value of C_{ij} .

The selection of the preferable alternatives is based on the utility value (8) of the alternative. The utility is calculated using a sum of weighted criteria normalized to the sum of one. The utility value is calculated as [30] :

$$U_i = \sum_{j=1}^n W_c \hat{C}_{ij} \quad (8)$$

where:

- W_c is the criterion's weight factor.

4 SOFTWARE TOOL IMPLEMENTATION

In order to test the functionality and performance of the methodology, a prototype software tool has been developed. The design of the software was carried out using Unified Modelling Language Diagrams (UML). The coding was performed in an object-oriented programming lan-

guage, using the .NET Framework™. A Relational Database Management System (RDBMS) has been implemented using the Oracle 9i Database. The database is used for managing and storing the data of the conducted experiments (Figure 5).

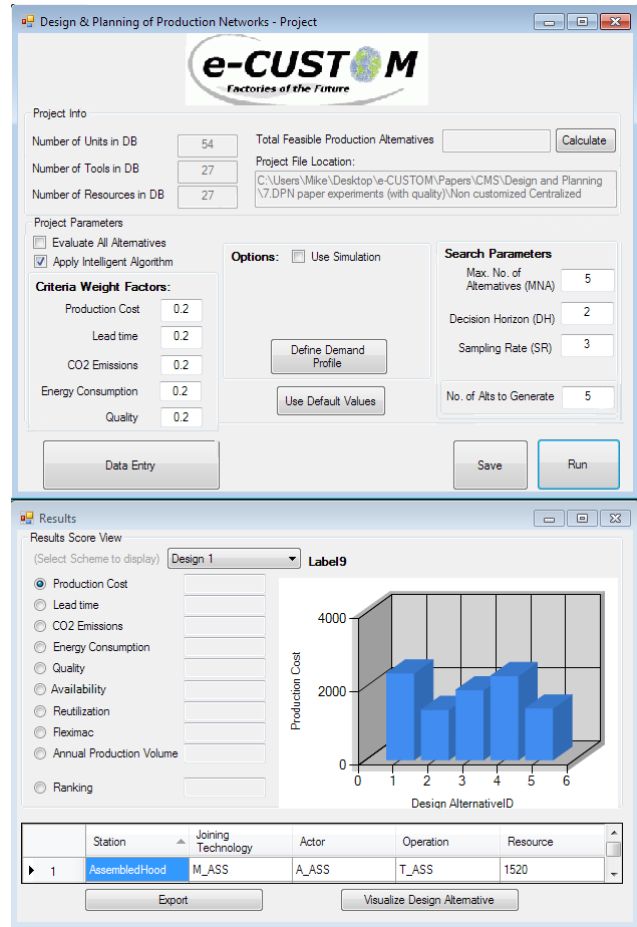


Figure 5: Software tool interfaces and visualisation of results in chart form.

The workstation used for performing the experiments was equipped by an Intel™ i7 3.4GHz processor, with 12GB of RAM that run at 1800MHz. The interfaces of the software tool comprise a set of Graphical User Interfaces (GUIs). The GUIs allow the required data entry, and the selection of the criteria weight factors. The user of the software tool is provided with the ability to select between the exhaustive search and intelligent search algorithm functionalities, and define the search parameters (MNA, DH and SR). If the intelligent algorithm is selected, the tool can generate a user-defined number of alternatives and visualise their performance in the form of bar charts (Figure 5). The visualisation depicts the resource assignments and operations designated for each product component and subassembly. The assignments are also stored in database tables for further manipulation. Moreover, the tool has the capability of automatic generation of Discrete Event Simulation (DES) models. The DES models are simulated in an integrated commercial simulation software suite. The user can designate the demand profile for the examined product and simulate its performance against this demand profile.

5 AUTOMOTIVE INDUSTRIAL CASE

The products, resources and dataset used in the presented case study are coming from a European automotive manufacturer. The car hood structure and the supply network configuration are described in Chapter 2 above. The resource characteristics include the processing time, setup time, Energy Consumption, Mean Time Between Failure

(MTBF) and Mean Time To Repair (MTTR), payload, unit-tool interface. Moreover, each one of the supply chain partners is classified with a quality indicator that takes values in the range of [0-100]. The quality classification is calculated based on the average quality of the components that the partners supply, and on their respect of due dates.

6 RESULTS AND DISCUSSION

A series of computer simulation experiments has been performed for the evaluation of the manufacturing and transportation schemes. The evaluation was performed according to the degree of customisation, for the alternative network configurations.

Figure 6 depicts the Number of Alternative schemes for the different Degrees of Customisation (DoC). Finally, Figure 8 displays the required computation time required for the execution of the experiments. Table 1 includes the dataset used for the experiments. The first column contains the task required for the manufacturing and assembly of the hood components, the second column contains the supply chain partner that can perform the task, the third includes the resources that can perform the tasks and finally, the fifth column includes the processing time of the task.

Task	Supply Chain Partner	Recourse	Processing time (min)	Description
T _{HF}	P_1	RP1_1_1	0.7	Hood Frame (HF) production
	S_6	RS6_1_1	1	
T _{HS}	S_3	RS3_1_1	0.5	Hinge Support (HS) production
	S_4	RS4_1_1	1	
	S_7	RS7_1_1	1.5	
T _{LS}	S_3	RS3_1_2	0.5	Lock Support (LS) production
	S_4	RS4_1_2	0.8	
	S_5	RS5_1_1	1	
	S_6	RS6_2_1	0.7	
T _{EXC}	P_1	RP1_1_2	1	External Cover (EXC) production
	P_2	RP2_1_1	0.6	
T _{WCC}	S_1	RS1_1_1	2	Wrap Cast Carbon (WCC) production
	S_2	RS2_1_1	1.6	
	S_5	RS5_2_1	2	
	S_7	RS7_2_1	1	
T _{BAS}	P_1	RP1_1_3	15	Assembly of the basic Hood (BAS)
	P_2	RP2_1_2	20	
T _{AWC}	S_1	RS1_1_2	20	Application of the Wrap Cast Carbon to the Hood (AWCC)
	S_5	RS5_2_2	30	
	D_1	RD1_1_1	480	
	D_2	RD2_1_1	320	
T _{ORN}	D_3	RD3_1_1	250	Ornament (ORN) production
	S_2	RS2_2_1	30	
	S_3	RS3_2_1	32	
	S_5	RS5_3_1	40	
T _{AOR}	S_7	RS7_3_1	20	Assembly of the Ornament to the Hood (AOR)
	S_4	RS4_2_1	25	
	S_1	RS1_2_1	18	
	S_6	RS6_3_1	20	
T _{AOR}	D_1	RD1_2_1	30	Assembly of the Ornament to the Hood (AOR)
	D_2	RD2_2_1	40	
	D_3	RD3_2_1	35	

T: Task, P: Plant, S: Supplier, D: Dealer, RP: Plant Resource

Table 1: Tasks, Supply Chain Partners, Resources and Processing Time for the Customised Car Hood Case Study.

The parameters of the conducted experiments are included inside Table 2. The first column is the number of the experiment. The second column "Degree of customisation" (DoC), indicates the product variant used for the experiment, namely, L1, L2a, L2b, L3 and L4. Finally, the remaining five columns contain the calculated values for the used criteria.

The weight factors of the criteria (W_{PC} , W_{LT} , W_{CO_2} , W_{EC} and W_Q) are used to express the objectives of the evalua-

tion. The weight factors get values between in the range [0-1], according to the relevant importance of the criterion. In addition, the sum of the weight factor must always be 1. The weight factors used in the conducted experiments are 0.2 for all the criteria. Therefore, the selection of the best alternative takes equally into consideration all the indicators.

No.	DoC	Production Cost (€)	Lead Time (min)	CO ₂ emissions (kgr of CO ₂)	Energy consumption (MJ)
1	L1	667.26	14.03	610.80	14,659
2	L2a	1357.02	19.74	782.00	18,768
3	L2b	1354.62	24.75	1028.0	24,072
4	L3	1866.37	28.10	1029.6	24,710
5	L4	2185.21	28.93	907.6	21,782

Table 2: Experiments and results for the Decentralised Network configuration.

The number of alternatives was calculated for the decentralised and centralised network configurations for the different degrees of customisation. The total number of alternatives for each scenario is included inside Table 3. A combinatorial explosion occurs when the degree of customisation increases. Thus, the utilisation of the intelligent algorithm is required for the identification of a good solution to the manufacturing and transportation decision problem.

Degree of Customisation	Number of Alternatives	
	Decentralised	Centralised
L1	792	288
L2a	20.592	1.728
L2b	20.592	1.728
L3	535.392	10.368
L4	13.920.192	62.208

Table 3: Number of alternatives for the different Degrees of Customisation and for the centralised and decentralised network configurations.

The diagram in Figure 6 displays the number of alternatives for the five examined degrees of customisation and for the decentralised and centralised network configurations.

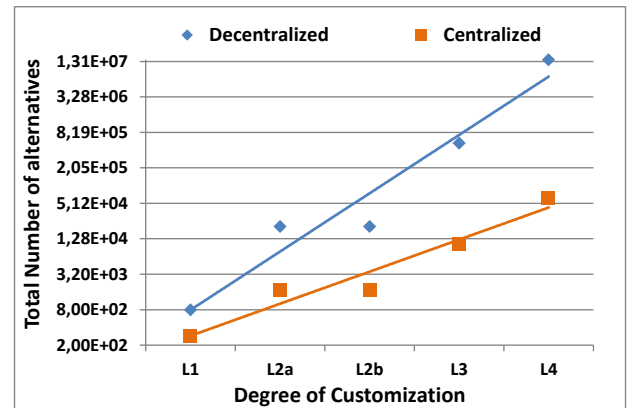


Figure 6: Number of Alternative vs. Degree of Customisation for the Decentralised and Centralised network configurations

The centralised scenario values are depicted by the orange exponential trend line, and the decentralised by the blue. Both lines display a positive correlation. The number of alternative schemes increases exponentially as the degree of customisation increases. Moreover, a deviation

is observed between the trend lines as the degree of customisation increases. The alternatives for the decentralised production network increase with a higher trend than in a centralised scenario.

Further to that, a comparison can be made between the required computation time for the execution of the experiments and the Degree of Customisation (DoC). Table 4 contains the computation time for the execution of the experiments. The values represent the exhaustive and intelligent search methods for the different network configurations.

DoC	Computation time (sec)			
	Exhaustive Decentral.	Exhaustive Central	Intelligent Decentral.	Intelligent Central
L1	30	22	214	127
L2a	190	27	215	170
L2b	229	26	210	172
L3	4532	90	226	135
L4	134712	510	228	139

Table 4: Computation time for the different Degrees of Customisation, for the centralised and decentralised network configurations, and for the exhaustive and intelligent search methods.

As seen in Figure 7, Figure 8 and in Table 3 and 4, a combinatorial explosion occurs in the number of alternatives in case the customisation degree increases. For the variant L4, the alternatives become $13,92 \times 10^6$ from 535×10^3 of the L3 case. Therefore, the use of an exhaustive search is prohibited due to the required computation time [25].

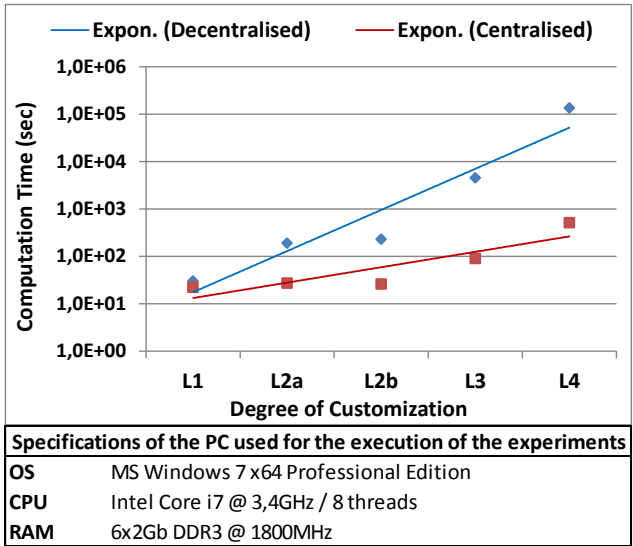


Figure 7: Computation time for the execution of experiments for the Centralised and Decentralised network Configurations and for the different Degrees of Customisation, using the exhaustive search.

Moreover, the intelligent search algorithm for the decentralised and centralised cases case displays no sensitivity as the degree of customisation increases. The required computation time for the intelligent algorithm ranges from 139-228 seconds regardless the number of alternatives. The execution of the experiments using the intelligent algorithm significantly reduced the computation time. Comparing the required time between the L1 and L3 experiments, the intelligent search yielded results 24,04 times faster than the exhaustive search. In the case of the L4 variant, the intelligent method was 596 times faster than the exhaustive. The deviation in the utility value between the

alternative with the maximum utility value and the one that was produced by the intelligent search is therefore acceptable, taking into consideration the computational effort.

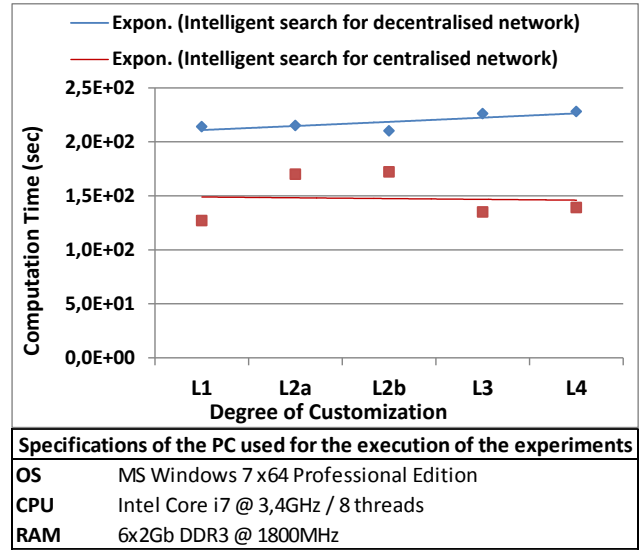


Figure 8: Computation time for the execution of experiments for the Centralised and Decentralised network Configurations and for the different Degrees of Customisation, using the intelligent search.

Furthermore, the analysis of the results of the experiments included in Figure 9 - Figure 12 depicts the following observations. The comparison of the values of the diagrams is performed using the relative difference (in percentage) of the values according to the five degrees of customisation (L1, L2a, L2b, L3 and L4). The relative difference is calculated using the following equation:

$$\Delta V = \frac{V_2 - V_1}{V_2} * 100\% \quad (9)$$

where:

- V_2 and V_1 the calculated values of the criterion for the different degrees of customization.

Based on Figure 9, the production of the variants L2a and L2b require 50.83% and 50.74% more production cost respectively compared to the variant L1. The production of the variant L3 requires 64.25% more cost compared to the variant L1. Additionally, the production of the variant L4 requires 69.45% more cost compared to the variant L1. The differences in the values are due to the increased number of processes and transportation distances required, as the degree of customisation rises.

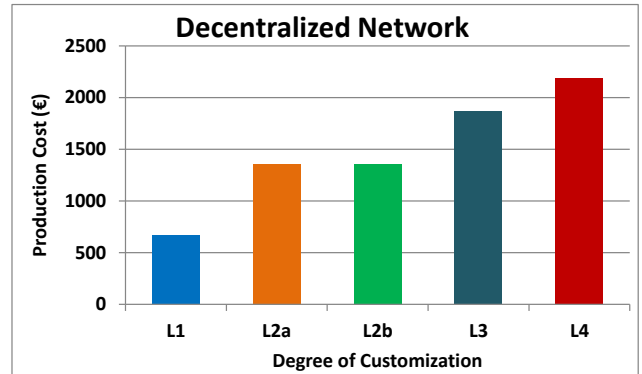


Figure 9: Production Cost vs. Degree of Customisation for the Decentralised Network Configuration, for the best alternatives.

Based on Figure 10, the production of the variants L2a and L2b display 28.93% and 43.31% respectively more lead time compared to the variant L1. The production of the

variant L3 requires 50.07% more lead time compared to the variant L1. In addition, the production of the variant L4 requires 51.5% more lead time compared to the variant L1.

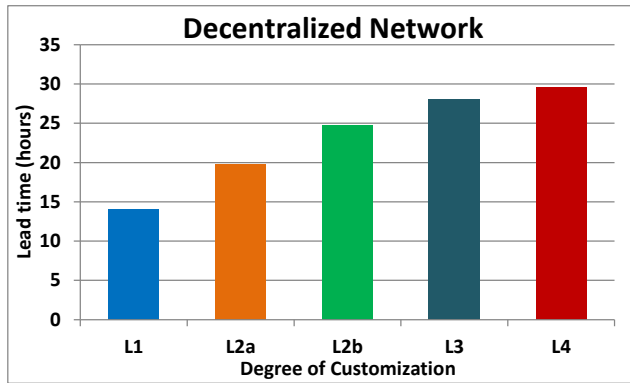


Figure 10: Lead Time vs. Degree of Customisation for the Decentralised Network Configuration, for the best alternatives.

Based on Figure 11, the production of the variants L2a and L2b are 21.89% and 40.58% respectively less environmentally friendly regarding the CO₂ emissions compared to the variant L1. The production of the variant L3 is 40.68% less environmentally friendly regarding the CO₂ emissions compared to the variant L1. Additionally, the production of the variant L4 requires 32.7% more CO₂ emissions compared to the variant L1. Moreover, in the case of the L4 variant, a decrease in the values of CO₂ emissions and energy consumption, is observed. The reason for the reduced indicators is due to the fact that the application of the second ornament and of the wrap cast carbon is performed at an OEM plant. This requires less energy consuming, and no additional transportation. The calculation of the CO₂ emissions is performed considering the emissions due to transportation, without including the processing of the raw materials.

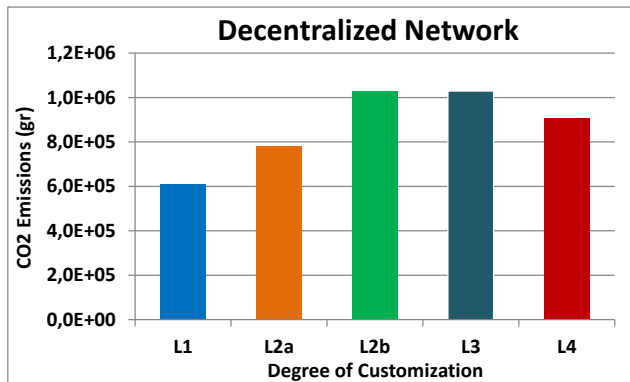


Figure 11: CO₂ Emissions vs. Degree of Customisation for the Decentralised Network Configuration, for the best alternatives.

Furthermore, based on the bar chart of Figure 12, the production of the variants L2a and L2b is 21.89% and 40.58% respectively, less environmentally friendly regarding the energy consumption, when compared to the variant L1. The production of the variant L3 is 40.68% less environmentally friendly, regarding the energy consumption compared to the variant L1. The production of the variant L4, requires 32.71% more energy consumption compared to the variant L1. The calculation of the energy consumption derives from the production and transportation requirements, and not from the energy required for the procurement of the raw materials.

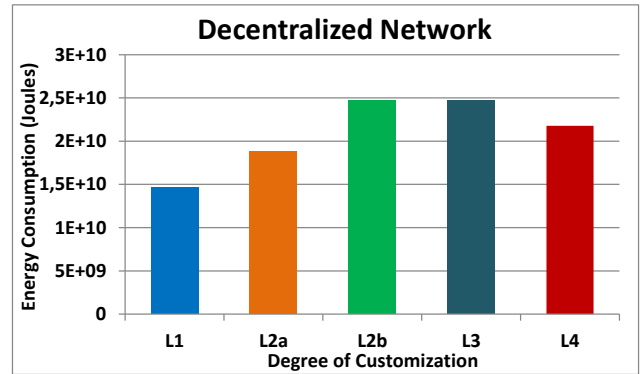


Figure 12: Energy Consumption vs. Degree of Customisation for the Decentralised Network Configuration, for the best alternatives.

A comparison of the calculated utility values that derived from the exhaustive search and the intelligent algorithm for the decentralised network configuration, is presented. The diagram in Figure 13 contains a comparison between the Utility Values of the best alternatives (blue line), the average utility value (red line) for the exhaustive search, and the utility value of the intelligent search (green line) for the five degrees of customisation. The declining trend line for the maximum utility is attributed to the fact that customisation has a negative impact to the selected parameters (cost, time, CO₂ emissions and energy consumption). In addition, a comparison between the maximum utility values with the utility values provided by the intelligent search is performed. A difference of 19.08% is calculated for the variant L1, 15.13% for the variant L2a, 11,31% for the variant L2b, 20,29% for the variant L3, and 8.72% for the variant L4, in favour of the exhaustive search. The intelligent algorithm provided high quality solutions, with significantly reduced computation effort. Finally, the relative difference in the utility value between the intelligent algorithm and the average utility of the exhaustive search were -21.62% for the variant L1, -30.83% for the variant L2a, -34,15 for the variant L2b, -11,48% for the variant L3 and -29.95% for the variant L4, all in favour of the intelligent search algorithm.

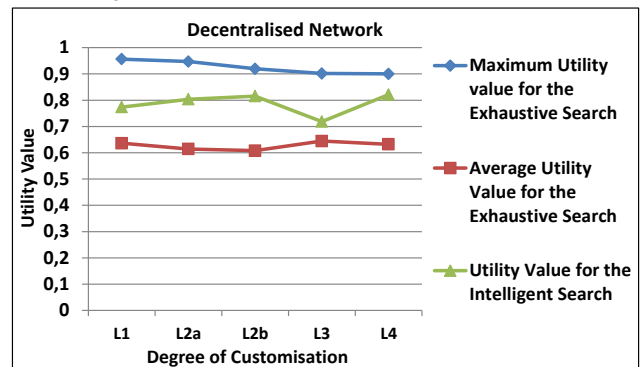


Figure 13: Utility Value for the Exhaustive and Intelligent Search for the Degrees of Customisation for the Decentralised network configuration.

7 CONCLUSIONS AND OUTLOOK

The presented methodology can support the decision makers during the configuration of the supply network. The deriving configurations take into consideration cost, time and quality indicators, as well as Energy Consumption and CO₂ Emissions. The results revealed a direct relation between the degree of customisation and the cost, time and environmental impact. Especially in the case of the L3 and L4 degrees of customisation, the impact was significantly higher than in the case of the basic, non-customised prod-

uct (L1). The addition of the customisation options (ornament and wrap cast carbon), imposes a number of additional processes and transportation routes. This increases the required cost, lead time and environmental impact of the final product. Additionally, the required computation time and the degree of customisation are directly related. The computation time in cases where the number of alternative schemes is high, requires the use of the intelligent search algorithm. The intelligent algorithm can provide high quality solutions by greatly reducing the computational burden.

Future work will focus on extending the capabilities of the methodology, incorporating the selection of different types of materials and transportation means. In order to further support the design of the manufacturing network, additional flexibility criteria will be calculated. The evaluation of the schemes will be performed against a demand profile, coming from a European Automotive Manufacturer, through an integrated simulation suite. Moreover, additional environmental indicators will be included for the evaluation of the alternative schemes. The additional indicators will include environmental impact of diverse raw materials, toxic emissions, and eutrophication metrics. In order to achieve the accurate calculation of the environmental indicators, a Life-Cycle Assessment (LCA) software tool will be integrated. Further to that, a web-based application will be embedded for the accurate calculation of the transportation distance (e.g. the Google Maps API). The OEM (user of the tool) will select from the map the location of the OEM Plants, Suppliers and Dealers or enter their coordinates (longitude, latitude). The distance will be automatically calculated, taking into consideration the optimum routes (shorter distances) and the constraints of road transport regulations (speed limit etc.).

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