Multidimensional Design Assessment Model for eco-efficiency and efficiency in aeronautical assembly processes

E.J. Lourenço
INEGI - Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial
Porto, Portuga
elourenco@inegi.up.pt

M. Oliva
Airbus
Seville, Spain
manuel.oliva@airbus.com

M.A. Estrela
ISQ - Instituto de Soldadura e Qualidade
Oeiras, Portugal
MAEstrela@isq.pt

A.J. Baptista
INEGI - Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial
Porto, Portugal
abaptista@inegi.up.pt

Abstract* – *This manuscript presents a novel framework, the Multidimensional Design Assessment Model, which encompasses a multi-criteria approach to efficiency, eco-efficiency and costs assessment for a given design system in aeronautical industry production. The framework is established by adopting Design-for-X and Multi-Layer Stream Mapping approaches, based on Lean Thinking, for efficiency assessment and adopting modules of ecoPROSYS to eco-efficiency assessment. A real case study from aeronautical sector is given to demonstrate the approach, for the assembly of aircraft structure Horizontal Tale Plane, where different results are presented and discussed for each dimension of analysis and how improvement strategies can be designed.

Keywords—eco-efficiency and efficiency assessment, multi-dimensional process design, aeronautical manufacturing

I. Introduction

Aeronautical sector face today increased challenges regarding climate change mitigation, moreover since the outlook for flight transportation is to increase in the future. In recent years the overall design of novel aircraft models, started to include, in a more detailed level, environmental impact assessment as a major consideration, which influences decisions made at the highest levels, including long-term planning by the company's management team, down to day-to-day operations at its production, customer support and other facilities located around the world. Such planning and projects show the commitment of aeronautical manufacturers to enhance air travel's eco-efficiency by initiatives that extend throughout the entire lifecycle of an aircraft, i.e., considering the design and production phases to its in-service operation and final dismantling. The entire lifecycle study is involved in the project design, including the industrialization stage of an aircraft and its level of environmental impact. In this context, new methods and frameworks are required, to improve the decision-making process, for design teams that need to value aspects influencing sustainability behaviour of products and processes [1].

A. State of the art

In order to manage the complex design process, aircraft manufacturers have been adopting advanced design management approaches, such as Collaborative Engineering [2]. Such approach promotes the integration of design teams, both functional and industrial, to assume a unique deliverable - iDMU (industrial Digital Mock-Up) rather than delivering a product DMU. The iDMU enables, also, intensive use of PLM (Product Life Cycle Management) tools to perform virtual manufacturing and therefore to substantially improve assurance of "errors free" results in the shop floor. Ultimately, by exploiting the iDMU, namely the full definition of the manufacturing activities, it is possible to feed work instructions to the shop floor [2]. Airbus Defence & Space had undertaken a project to implement the iDMU concept, that can support the industrialization process of a medium size aerostructures, as a key technology for the industrialization of aircrafts assembly lines, and it was confirmed the potential of the iDMU to improve the industrial design process in a collaborative engineering environment, through enhanced and improved communication [2, 3]. An iDMU gathers all the product, processes and resources information, both geometrical and technological to model a virtual assembly line. As a result, an iDMU provides a single platform to define and validate the assembly line industrial design. One of the main benefits of an iDMU is the reutilization of its elements in the multiple and different tasks of the assembly line industrial design [3].

According to [4] a digital eco-factory is a virtual factory on which a production scenario is examined from several viewpoints. When a digital eco-factory is used, green performance of the planned production scenario is examined in addition to productivity and manufacturability at the same time with various granularities such as machine level, product level and factory level. This concept, of digital eco-factory, can somehow, relate with Airbus's Collaborative Engineering approach to deliver a unique deliverable – iDMU. As in the iDMU, to construct a virtual production line in a digital eco-factory requires the modelling of an actual shop floor and its components, including their activities. The virtual production line (this also may apply for assembly process) should emulate the structure of the shop floor in the actual factory. In these lines, all components such as machine tools, assembly machines, robots and workers should be configured as software agents. With such model, the operator of the digital factory can input configuration of the production line and production scenarios.

In terms of eco-efficiency, the complex interrelations between the economic and environmental performance dimensions in production systems create, sometimes, an incomprehensible "scenario" for decision makers, which may limit the translation of this strategic target into eco-efficiency improvement measures on a shop-floor level. Therefore, approaches such the one presented in [5] for a discrete-event simulation can be promising methods to solve this problem. The authors propose a decision support consisting of two elements:

- A novel discrete-event simulation approach that seamlessly integrates LCA with common economic evaluations by embedding the Ecoinvent LCI database, while considering all relevant eco-efficiency drivers within a production system;
- A system analysis and modelling procedure supporting its application and the identification of appropriate improvement measures.

Although the tool allows a good eco-efficiency assessment, the model lacks resource efficiency and operational performance assessment in order to, fully, support decision-making processes for assembly process design. Manufacturing, as for assembly processes, consists of transforming inputs (e.g. material, personnel and energy) into valuable outputs (e.g. products, components, structures), often together with undesirable outputs like different forms of waste and other emissions. Historically, manufacturing has been, and still is, an important driver for economic development. During the last two centuries, industrial revolutions lead to manufacturing in factories with higher volumes and productivity. The economic aspects are clearly in focus, yet factories are associated with diverse negative environmental and social impacts. In the last decades, lots of work has been done in order to minimize such impacts [6]. Manufacturing industry can reduce its impact by adopting eco-efficiency based approaches, namely via eco-design methods at design stage, which are increasingly viewed as key to sustainable and improved product development [7]. However, for eco-design approaches to be effective, and have a significant impact, the techniques need to de based on accessible design and engineering principles, which provide support throughout the design and manufacturing process. Despite the apparent benefits of eco-design, it is not clear if they have any real effect on product system developments, since it is not clear if these tools are used [7]. Despite the benefits of using eco-design techniques, such approach is not directly oriented for process nor assembly design, as these are mainly used for product development. Yet, the eco-design philosophy can be applied as an enabler to reduce the impacts within the assembly, by improving the assembly process design considering eco-design principles. Regarding good practices for sustainable manufacturing, [8] states, "the technical knowledge for eco-efficiency is largely available, however the difficulty is to put it into practice". Yet, there are more elements to consider when it comes to improve eco-efficiency and assessing environmental performance. In [9], a survey on Common Practices in Sustainable Aerospace Manufacturing is presented. The goal was to identify the gaps so that future efforts can be appropriately committed. The survey results identified that one major gap is in the little attention paid to component and final assembly. Furthermore, reuse and remanufacturing of components of retired systems can be considered value adding processes that can be included in the manufacturing process, however there is a seeming lack of attention paid to reuse and remanufacture. There are some instances of initiatives, such as the Airbus PAMELA end of life initiative. Therefore, and due to the mentioned above, the main goal of the new Multidimensional Design Assessment Model is to integrate and validate aspects as Eco-efficiency and, Resource and Operational Efficiency in new process design definition, aligned with multi-dimensional design integration by adopting Design-for-X approaches based on Lean Thinking [10]. These core methods, that are part of the new framework, consist in the integration of innovative methodologies, namely ecoPROSYS and Multi-Layer Stream Mapping (MSM). ecoPROSYS is an integrated methodology which allows the evaluation and assessment of eco-efficiency performance [11]. MSM is a lean based method, developed to assess overall efficiency performance [12]. The new design assessment model developed in H2020 CleanSky 2 on the topic "Eco Efficient factories of the future" [13], created in order to enable the performance assessment of four main design domains:

- Resource Efficiency;
- Eco-efficiency;
- Operational Performance; and
- Costs.

The manuscript is organized in four sections, introduction, novel methodology description, aeronautical application case study and results, and final remarks, where the main conclusions of the work are extracted.

II. Multidimensional Design Assessment Model

A. Overall model structure

The overall aim of eco-efficient manufacturing approaches and efficient use of materials and energy is to propose eco-efficiency solutions, based on emerging technologies and methods to achieve a more efficient use of material and energy resources in the plant, focusing on manufacturing and assembling processes, while ensuring the high productivity rates and less costs and environmental impacts. Reduced resources consumption include time, raw materials, waste materials, consumables, pneumatic and hydraulic fluids.

The Multidimensional Design Assessment Model, which encompasses the Eco-efficiency and Operational Efficiency Assessment, was developed to support decision-making process for high-complexity assembly processes in aircraft production. The methodology base roots comprise different original frameworks, namely: Lean Design-for-X approach for multidimensional design assessment [10]; and MAESTRI Efficiency Framework devoted to cross-link the assessment of eco-efficiency and efficiency in manufacturing processes [14]. All the rationale for supporting the decision-making in process design definition, integrating multiple criteria aspects and the necessary calculations for process design indicators are presented in this manuscript. In Fig. 1, an overview of the Multidimensional Design Assessment Model structure is presented, and in general the main data inputs for the model and respective outputs, i.e., results are depicted. Additionally, the Total Efficiency Index - TEI [14], which is calculated for each phase of the assembly process under analysis, is part of the results of the model.

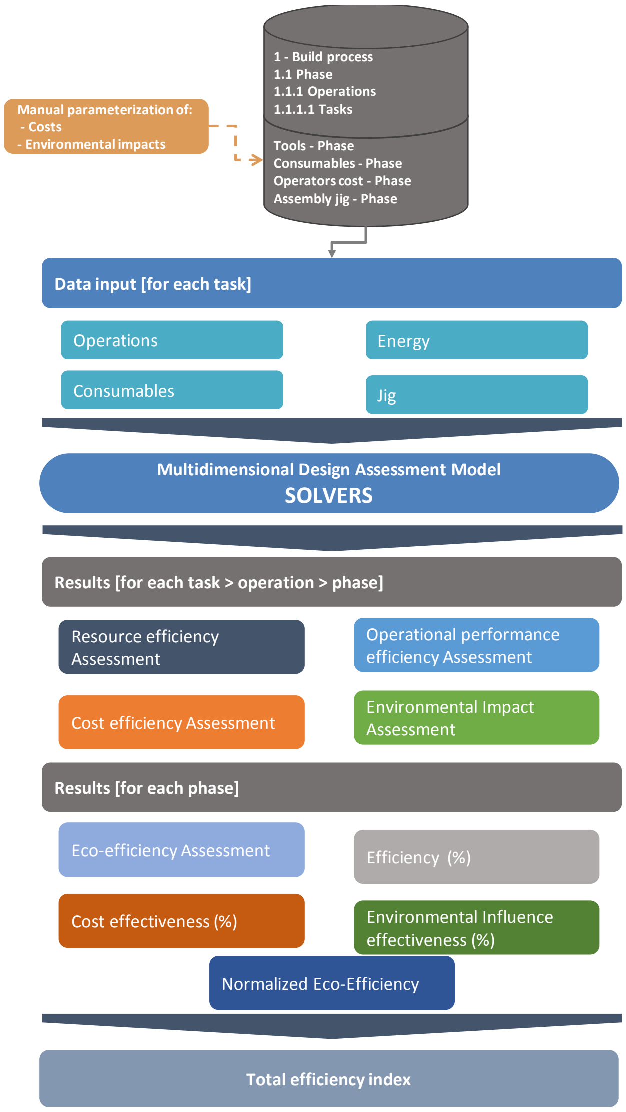

Fig. 1. The Multidimensional Design Model diagram

The logic behind this index is to combine two fundamental efficiency aspects, namely eco-efficiency, which considers the ecology and economy aspects, and resource and operational efficiency, which considers the Value Added (VA) and Non-Value Added (NVA) activities aligned with the Lean Principles from MSM - Multi-Layer Stream Mapping [12].

The model follows a bottom-up approach, in the sense that the data input is done at the most elementary level, i.e. task level, enabling to get results for all levels, namely: Tasks > Operations > Phase. Eventually, with such data and results structure it is possible to integrate the phase results and assess the Build Process. Moreover, it is possible to compare the performance of the different tasks, operations and phases. The major limitations of the Multidimensional Design Model are related with data quality and with the wide range of assumptions that can be made in order to define the value and the non-value adding portions. If these are not well established and justified, the results interpretation/evaluation may be misleading. The lack of organization's structured/formal standards for defining assembly processes and tasks, and the lack of available input data, can be a limitation for the implementation of the model, because if these are not well defined, the results can become unrepresentative or misleading. Additionally, if all data is not centralized and easily available, the implementation and deployment on the Multidimensional Design Model could be very time consuming and expensive.

The Multidimensional Design Model, encompasses several main modules, namely:

- Goal and scope definition;
- Data input (for each task);
- Results for each task, operation and phase;
- Integrated results.

The model is foreseen to adopt a modular approach, in the sense that after characterizing all tasks it is possible to build each assembly operation and consequently each operation.

B. Eco-efficiency and efficiency assessment tools

The ecoPROSYS approach relies on the use of a systematized and organized set of indicators easy to understand/analyse, aiming to promote continuous improvement and a more efficient use of resources and energy. The goal is to assess eco-efficiency performance in order to support the decision-making process and enable the maximization of product/processes value creation while minimizing environmental burdens. Eco-efficiency, the base concept of ecoPROSYS, measures the relationship between environmental and economic development of activities as sustainability aspects that evidence more value from lower inputs of material and energy and with reduced emissions. Eco-efficiency, commonly, expressed by the ratio between value and environmental influence. The methodology ecoPROSYS is aligned with the eco-efficiency goals and principles defined by the World Business Council for Sustainable Development. From a conceptual point of view, in this methodology the indicators, lead to decision support indicators, which are generated by a combination of three components: Environmental Performance Evaluation (EPE); Life Cycle Assessment (LCA); and Cost and Value Assessment [11].

The MSM is a Lean based resource efficiency assessment methodology, which takes into account the base principles from the Value Stream Mapping (VSM). Namely the value streams, in order to identify and quantify, at each stage of the process system, all VA and NVA actions, as well as, all types of waste and inefficiencies along the production system [12]. Therefore, the basic principle of the MSM relates to Lean Principles, i.e. clear definition between value and waste - enables to calculate efficiency. The MSM approach intends to encourage achieving maximum efficiency, (i.e. 100%) and continuous improvement mind-set. Moreover, unlike the VSM that focuses mainly on the VA and NVA of the time dimension, MSM focus is to assess the overall performance, by taking into account the efficiency of each manufacturing or assembly process parameter (e.g. time, energy, water and raw material) associated to one or more process steps. The goal is to: (i) provide an efficiency integration analysis; (ii) identify inefficiencies in a very direct and visual manner; (iii) support decision-making; and (iv) help prioritize the implementation of improvement actions based on resource and operational efficiency, as well as related cost [11].

Other tools that address the extension of VSM to incorporate additional criteria, namely, energy-related and sustainable aspects focused on environmental performance are used to evaluate economic, environmental and social sustainability performance in manufacturing, but without the flexibility and multi-domain integration provided by MSM, along an original and modular scorecard.

An important aspect of the new Multidimensional Design Model relies on the integration of eco-efficiency and efficiency assessment methodologies (Fig.2). The outline of the integration of ecoPROSYS and MSM, which concerns the exchange of information, results and cross-parameterization inputs between efficiency and eco-efficiency assessments, which corresponds to the central objective of the model. The approach followed to integrate ecoPROSYS and MSM is primarily through the combination of the eco-efficiency and efficiency results rather than the fusion of results (Fig. 2). Such approach enables support decisions, and the new integrated results, namely the:

- Total Efficiency Index - New metric of obtained by integrating eco-efficiency with efficiency metrics;
- Environmental and Cost / Value Performance - Indicator based on real (total) and target (VA) figures;
- Normalized Eco-efficiency - Combination of results from real (total) and target eco-efficiency ratios (VA);
- Environmental Influence and Costs of the VA and NVA activities: These are obtained by integrating costs, environmental impacts and efficiency results based on MSM approach.

These results, in addition to support a more complete and informed decision-making process, regarding sustainable development, also play an important role when it comes to reporting results through score-cards/dashboards within the Multidimensional Design Assessment Model. The combination of the efficiency and eco-efficiency results will enable to assess the effectiveness of the eco-efficiency performance improvement. This will be done by monitoring deviations between the real eco-efficiency (real economic value over real environmental influence) and targeted, i.e. VA eco-efficiency (target economic value over target environmental influence). During the normalisation of the eco-efficiency results, within the model, the economic or monetary value and environmental influence efficiencies are also calculated. The value effectiveness is determined by the ratio between the real and the target value (VA), while the environmental influence effectiveness is calculated by the ratio between the real and the target environmental influence (VA). Both efficiency results are given as percentages. These results will support the decision making process, by helping on the quantification of the gap between real and target results for the value and environmental aspects [14].

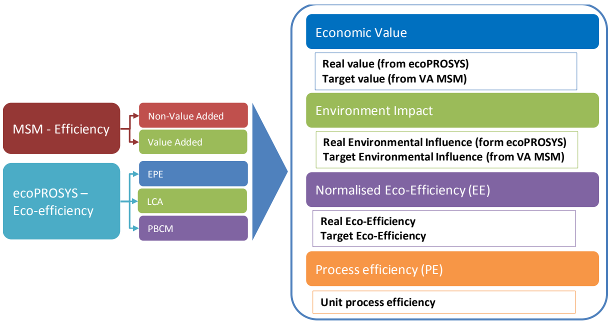

Fig. 2. Efficiency Framework general diagram [14]

Consequently, the Efficiency Framework main outcome is related to the ability of evaluating if eco-efficiency performance variation is due to higher or lower environmental influence, or due to higher or lower economic value. In practice, this results from the distribution variance that occur on two major axes: the efficiency and eco-efficiency.

Next figure presents in a graphical way this distribution (Fig. 3). The main characteristics and insights related to the distribution of Efficiency Framework Quadrant results distribution are:

- Quadrant I - The production system generates an acceptable economic value considering the environmental impacts caused by its activities. Then, considering the current technological settings, it has a low improvement potential.
- Quadrant II - The acceptable eco-efficiency performance is likely to be led by low environmental impacts related to the production system activities. Improvement actions to increase the economic value generation are advisable, namely by improving process parameters efficiency.
- Quadrant III - The production system presents low performance at all levels. The implementation of improvement actions is extremely recommended.
- Quadrant IV - Despite presenting acceptable efficiency, the production system is not generating the expected value. Technological changes are also recommended to decrease environmental impacts.

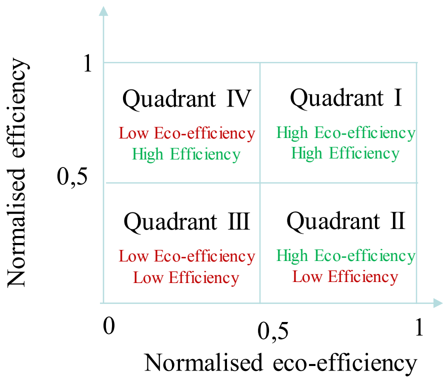

Fig. 3. Efficiency Framework quadrant diagram.

The integration of the Efficiency Framework tools is achieved by the combination of the results, focusing a given production system assessment and main indicators to analyse associated in the model (Fig. 4). For the case of aircraft assembly, a hierarchical in followed from the higher level Build Process, Phase, Operation and finally the individual Task. Four main domains are considered: Energy indicator, Operations indicators, Consumables indicators and Jig use (capital asset).

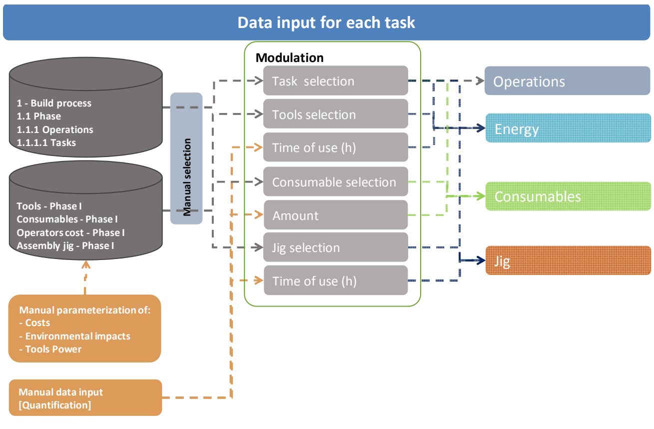

Fig. 4. The Multidimensional Design Model – Data input and modelling stage

Since the Multidimensional Design Model adopts a modular approach, linking namely MSM and eco-efficiency results based on ecoPROSYS analysis, the results also adopt as basis a modular approach, combined at the end via quadrant diagram analysis and specific scorecards. In Fig. 5, it is presented the schematic articulation of the results, as a bottom-up approach from Task to Operation, and from Operation to Phase.

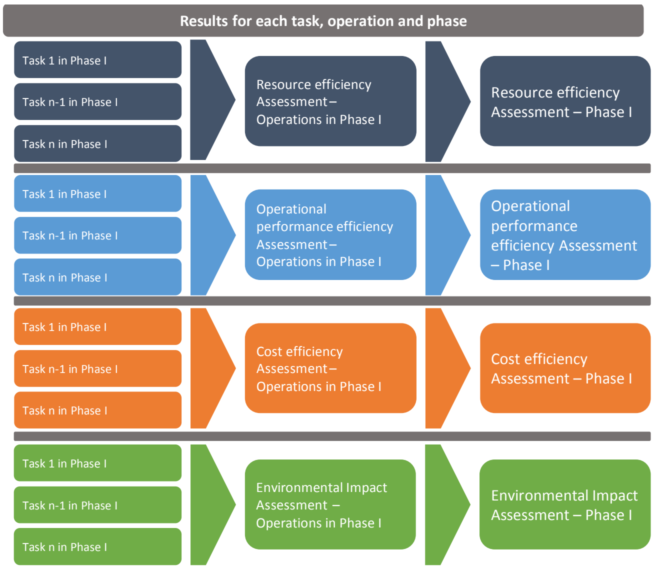

Fig. 5. The Multidimensional Design Model – Results by production level

III. AERONAUTICAL APPLICATION CASE

A. *Goal and Scope definition*

The chosen example for this application case was based on a real assembly operation of Airbus Horizontal Tale Plane (HTP) aircraft structure (Fig. 6). For confidentiality and business related reasons the data used and respective results are distorted, but the coherence of the analysis and demonstration conclusions for the new Multidimensional Design Model are not affected.

The first step is of the Multidimensional Design Assessment Model is to set the scope, define the boundaries of the analysis and the goal of the assessment. This phase should denote:

i. the product system intended to be assessed (in this case the assembly phase);

ii. the functional unit and;

iii. the system boundary.

The functional unit, according to the ISO 14040:2006 [15], is defined as the quantified performance of a product system. In other words, the functional unit provides a reference to which all inputs and outputs are related, i.e., a metric reference for the resource efficiency, environmental and cost data. For instance, the functional unit for the assembly process of a HTP could be defined as - “The assembly of one HTP going through phase I”. The system boundary should define the unit processes to be included in the system under analysis. For this particular case, i.e., assembly, the system boundaries should be defined in order to include all operations and respective tasks that are within the phase I assembly sequence. The identification/delimitation of the operations that are part of the production system should represent the elementary flows (i.e. data for time, energy and resources) and define the limits of the system. In general, the boundaries defined for the Multidimensional Design Assessment Model should always follow a gate-to-gate approach, as the assessment focuses on the particular assembly phase and respective operations. Reading the goal, it is important to define “What are we trying to understand” and the intended application, along with the reasoning of the assessment. The scope of the assessment should ensure that the depth and detail of the assessment are compatible and sufficient to address the stated goal [16].

Finally, it is important to identify all the assumptions / considerations made during data collection (e.g. approximations/estimations for energy consumption based on nominal power) and/or while parametrizing the models (e.g. Labour costs are considered as average value (€/h)). This aspect is important in order to have a clear understanding of the results analysis.

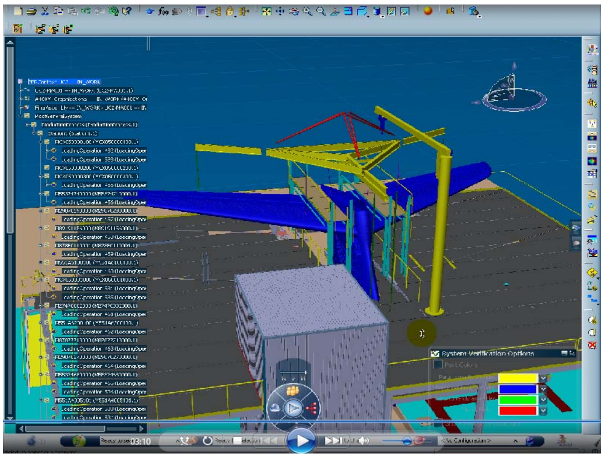

Fig. 6. 3D CAD model of the HTP assembly structure

B. *Data Input*

In order to enable a bottom-up approach, the data structure for the input data considered is built from the task up until the build process (Fig. 7). For this particular case several tasks are part of an operation; subsequently each phase has several operations. Ultimately, the build process of the HTP Assembly Process, encompasses four phases. With such data structure, and by entering the data (data input) at the task level, the Multidimensional Design Assessment Model is able to present results for all operations phase and build process. Such particularity of the model is mainly due to the capacity of the method to integrate results in a bottom-up approach.

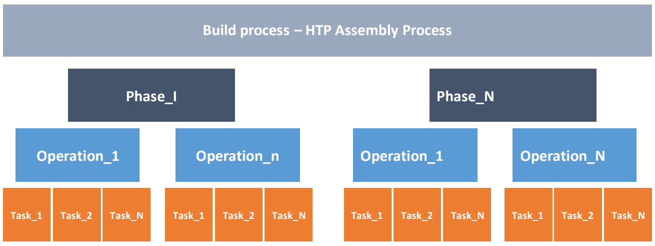

Fig. 7. Example of the data structure – Bottom-up approach

It is noteworthy that the model is flexible, in the sense that levels could be added or removed, and the model will provide the results to asses all Multidimensional Design domains. Nonetheless, in order to enable a bottom-up integration and assessment of results, all elementary data, i.e. lowest level data, should be entered as data input. However, in order to assess the performance of the four design domains, namely resource efficiency, eco-efficiency, operational performance, and costs, of all tasks, operations´ phases and the overall build process, the following data are required, namely:

- Operators cost rate (€/h)
- Power of each tool (kW)
- Power of the Jigs (kW)
- Energy costs (€/kWh)
- Energy Environmental Impacts (Single Score - Pt)
- Consumables costs (€/unit of consumable) - For all consumables
- Consumables Environmental Impacts (Single Score - Pt) – For all consumables

The cost rate of the operators is necessary to be parametrized. This information will enable to calculate costs of the operators in each task, operation, phase, and ultimately in the build process. For the labour costs, the approach uses the average cost, this will facilitate the parameterization, as among the assembly sequence different operators with different wages.

For the assembly tools, it is necessary to parametrize, i.e., quantify for each tool the power (kW). Additionally, the energy costs (€/kWh) and the Environmental Impacts (Pt). This data is the same for all tools as it is constant value. The jig parameterization requires the same information as the tools. Regarding the consumables, the same rationale applies. Yet, for each consumable it is necessary to define the costs (€/unit of consumable) and the Environmental Impacts (Pt). However, once this parameterisation is done there is no need to change this data, unless there is some kind of update in energy, material or labour costs. One other reason that may require change is if there is a change in the material of a consumable, or a tool is changed by one with different power, this could require updating the environmental impact value and probably the costs.

The parameterization of the tools and jig power and related energy costs, along with the consumables costs, are quite straightforward to understand and classify/quantify. The costs and power for the tools and jigs, and the costs for the consumables are quite simple, in the sense that Airbus has knowledge of these values. On the other hand, the environmental impacts calculations may be quite complex. Therefore, in order to reduce complexity and have an easily understandable and comparable environmental impact value, the model instead of considering impact scores broken out into categories, with no weighting at all, considers a weighted "single score". Such approach has the advantage of generating one, easy-to-communicate impact number, often expressed as "Points" (Pt). Accordingly, the Multidimensional Design Assessment Model uses a single score approach, which is aligned with Airbus vison, i.e. have a "standard" environmental impact value easy to understand by comparison and to evaluate.

With this is mind, the model will consider ReCiPe method, Hierarchist perspective, as this perspective is based on a consensus model, and this method has a substantially lower uncertainty of weighting process. The general idea of the datasets and respective environmental impacts for the Multidimensional Design Assessment Model, is to identify an available dataset within a free database that is equivalent to the materials and consumables used within the HTP build process and, subsequently, normalize the single score of the dataset to the unitary value of the consumable. For example, considering the "Aluminium material" as aluminium, it is possible, by taking into account the weight of an aluminium rivet, to have the equivalent single score (Pt) of an aluminium rivet used in the assembly process. This kind of approach/parameterization is to be applied to all consumables along the build process. After modelling all tools, jigs and consumables according to data inputs, and all the assembly tasks within the phase I of the HTP build process, all parameterization are finalized.

The final step is to classify the tasks as VA or NVA, since the Multidimensional Design Assessment Model focuses, as a key aspect, on the identification and quantification of all VA and NVA tasks. For this case study, the VA and NVA attribute is aligned with the allocation defined by Airbus process engineers. Consequently, the classification of the task as VA and NVA will be useful when analysing the results, in order to understand the amount of consumables, energy and respective costs and impacts that are VA and NVA. One important aspect to keep the results highly reliable is not to use weight allocation of criteria and assignment of VA and NVA activities. Nonetheless, if users make weight assumptions, these should be kept in mind when analysing the results, as the weight assumptions cloud generate misrepresent results. Therefore, if a weight criterion is used, the results without weight assumptions should also be presented, in order to avoid complete distortion of results interpretation.

C. *Results*

This section of the manuscript provides the results of the aeronautical application case, using the Multidimensional Design Assessment Model. The results of the model are presented for Resource Efficiency; Eco-efficiency; Operational Performance, and Cost efficiency and operation level – results which are based on the integration of results from task level, using a bottom-up approach.

In Fig. 8, a partial example of the resource efficiency (processed by MSM tool) for the tasks within Operation 1 is presented. Such elementary results at task level, enables to built-up the results for the operations, phases and ultimately for the build process, via integration of results. Moreover, such approach enables to compare performance between tasks within the same operation or different operations or even phases.

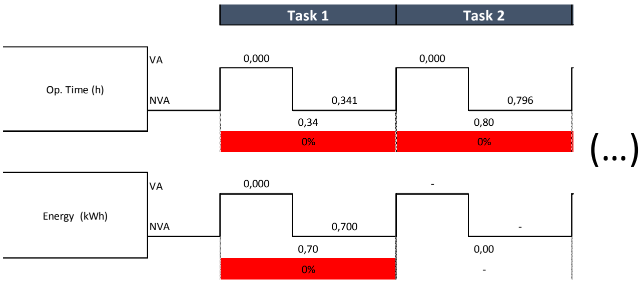

Fig. 8. Example for resource efficiency for the tasks within Operation 1

Due to the high number of tasks and variables, for instance 26 and 25 respectively, within each operation, there is an extraordinary detail of results, which are somehow complex to analyse, therefore, despite task results being indispensable, the overall idea is to analyse the results at operation level, and if necessary drilldown and have accesses to results at task level.

In table I, the integration of the task results from operation 1 and 3, are presented. With such results it is possible to compare the efficiency of the different variables within the same operation and analyse the differences between operations, for instance it is possible to understand that consumables use efficiency is subracial higher in operation 3. Additionally, it is possible to conclude that in both operations the jigs are used in NVA task, therefore the efficiency is 0%.

TABLE I. EXAMPLE OF RESOURCE EFFICIENCY ASSESSMENT FOR OPERATION 1 AND OPERATION 3 IN PHASE I

	OP1				OP3			
Resource efficiency	**VA**	**NVA**	**Total**	**Effi.%**	**VA**	**NVA**	**Total**	**Effi.%**
Op. Time (h)	1,02	6,94	7,96	12,9%	2,05	8,64	10,69	19,1%
Energy (kWh)	4,00	3,90	7,90	50,6%	1,35	2,60	3,95	34,2%
Consumables use	-	-	-	14,3%	-	-	-	44,4%
Jig Time of use (h)	0,00	6,00	6,00	0,0%	0,00	3,00	3,00	0,0%
Jig Energy consumption (kWh)	0,00	60,00	60,00	0,0%	0,00	30,00	30,00	0,0%
OP effi. %	-	-	-	**12%**	-	-	-	**19%**

Using the results form table I, these give place to the phase results, as the results for both operations are integrated. In the dashboard depicted Fig. 9 the resource efficiency assessment results are depicted in a visual manner and subsequently the integration of operation results makes up the phase result, via the integrations of overall resource efficiency of OP1 and OP3, which give place to the Phase I efficiency, i.e. 15%.

The advantage of looking into operation results, using the dashboard in Fig. 9, is that operation can be compared in a very swift manner and the overall phase result can be assessed. This kind of analysis meets the requirements set by Airbus, consequently the model enables such comparison of results and enables to have an instantaneous understanding of the assembly process resource efficiency. Ultimately, buy integrating results from several phases it is possible to assess the resource efficiency of the build process.

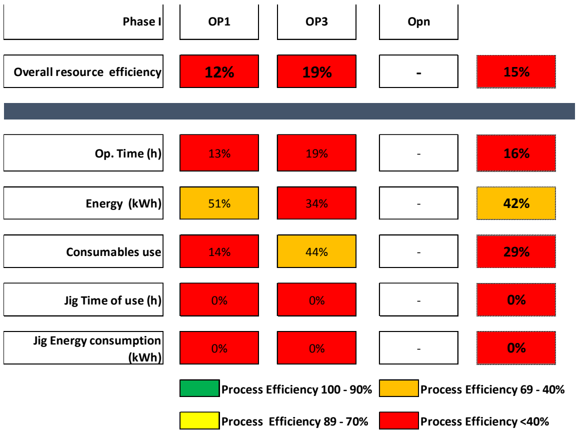

Fig. 9. Example of MSM Dashboard for resource efficiency assessment for operation 1 and operation 3 in Phase I

Regarding the cost efficiency, as mentioned it is build up by summing all VA and NVA costs within the operations 1 and 3. The costs related to each operation for each variable is also a result from the MSM approach. The result, as presented in TABLE II, enables a simple cost analysis, which address the value and non-value added costs, namely for labour, energy consumables costs and jig costs. Such results enable to support the decision making process in terms of prioritization for the implementation of improvement actions for cost reduction. For instance, despite the cost efficiency for a certain operation being higher than the other operations, it is important to always analyse in detail, and compare the NVA costs of the different operations, since the operation with higher efficacy could also be the one with higher NVA cost value. For example, in OP 3 despite the cost efficiency for the energy (34,2%) being lower than the consumables cost efficiency (51,9%) it is best to improve cost efficiency of consumables since it has a NVA cost value (13,00 €) higher than the energy costs (0,34 €). Therefore, a simple analysis enables to see which operations should be looked into in order to reduce NVA costs. Fig. 10, allow to analyse overall cost efficiency results and have a clear cost breakdown regarding VA and NVA.

TABLE II. EXAMPLE OF COST EFFICIENCY ASSESSMENT FOR OPERATION 1 AND OPERATION 3 IN PHASE I I

	OP1				OP3			
Cost efficiency	**VA**	**NVA**	**Total**	**Effi.%**	**VA**	**NVA**	**Total**	**Effi.%**
Labour Cost (€)	46,07	450,45	496,52	9,3%	92,14	302,01	394,14	23,4%
Energy Cost (€)	0,52	0,51	1,03	50,6%	0,18	0,34	0,51	34,2%
Consumables cost (€)	0,08	108,60	108,68	0,1%	14,00	13,00	27,00	51,9%
Jig use Cost (€)	7,80	0,00	7,80	100,0%	3,90	0,00	3,90	100,0%
Total	**54,47**	**559,55**	**614,02**	**8,9%**	**110,21**	**315,34**	**425,56**	**25,9%**

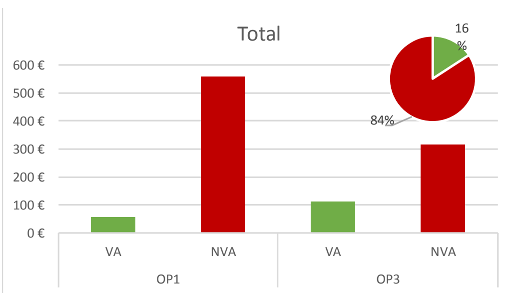

Fig. 10. Example of cost efficiency assessment for operation 1 and operation 3 in Phase I

The environmental impact assessment results follow the same rationale as the costs (see Fig. 11 and table III). Therefore, the previous statement is also valid for the environmental impact assessment. The results represent a clear breakdown regarding the environmental impacts that take place during VA and NVA tasks.

TABLE III. EXAMPLE OF ENVIRONMENTAL IMPACT ASSESSMENT FOR OPERATION 1 AND OPERATION 3 IN PHASE I

	OP1				OP3			
Environmental Impact	**VA**	**NVA**	**Total**	**Effi.%**	**VA**	**NVA**	**Total**	**Effi.%**
Energy Impact (Pt)	0,01	0,01	0,02	50,6%	0,004	0,007	0,011	34%
Consumables Impact (Pt)	0,02	72,25	72,27	0,0%	1,020	3,000	4,020	25%
Jig use Impact (Pt)	1,43	0,00	1,43	100,0%	0,717	0,000	0,717	100%
Total	**1,46**	**72,26**	**73,73**	**2,0%**	**1,741**	**3,007**	**4,748**	37%

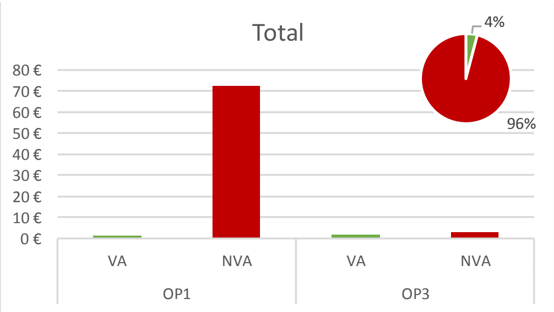

Fig. 11. Example of environmental impact assessment for operation 1 and operation 3 in Phase I

This kind of assessment is important to compare the costs and environmental impacts of different operations. In order to compute the phase costs or environmental impacts these results are fundamental. The charts are very useful as they are very intuitive to interpret. This kind of dashboard is also very useful for comparing environmental impacts results, as these are not so intuitive to understand as costs, for instance. The eco-efficiency results, for Phase I, are presented in Fig. 12. The eco-efficiency analysis enables to see the eco-efficiency performance in the Operation 1 and 3. Moreover, such analysis of eco-efficiency enables to understand, in an expedite manner, if the eco-efficiency performance is high or low. The economic dimension was calculated from costs considering assembly costs. The environmental aspects considered for the eco-efficiency assessment refer to the consumables and energy consumption.

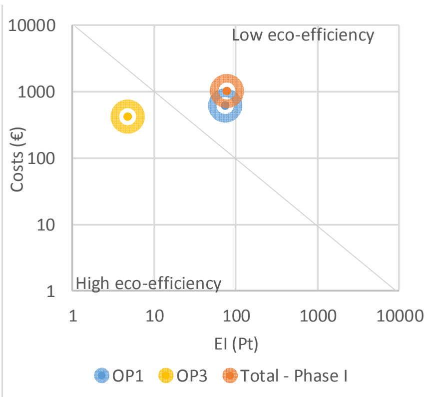

Fig. 12. Eco-efficiency Plot for Operation 1 and Operation 3 in Phase I

In order to calculate the TEI, macro indicator, the eco-efficiency ratios have to be calculated. Additionally, it is necessary to quantify the costs, value and the environmental influence for each task, as well as the targeted (VA) figures related with costs and environmental influence. Subsequently, it is possible to qualify the targeted (VA) eco-efficiency ratio for each task under analysis. These targeted values arise from the VA portion quantified through MSM. Therefore, the quantification of eco-efficiency performance and efficiency performance of each assembly step is necessary to calculate the TEI for each operation. With these results it is possible to calculate the cost and environmental influence effectiveness in order to obtain the normalization of eco-efficiency.

In Fig. 13, it is possible to evaluate the TEI, as well as the effectiveness of the value dimension in costs and environmental impacts for each operation. It is possible to conclude that operation 3 has a higher TEI. The Phase I TEI is also calculated, for this application case the TEI for Phase I is 2%.

Despite the TEI results, the Multi-Dimensional Design Assessment approach enables to assess, in a quadrant diagram, the efficiency and eco-efficiency performance for each operation. For this particular case, and data considered, both operations have relatively low eco-efficiency and efficiency performance, as presented in Fig. 14. Nonetheless, such diagram allows also to define the strategic route for improvement actions in the assembly system, for instance, since OP1 has very low normalized eco-efficiency, the 1st step would be to improve this dimension and then improve OP1 efficiency. For OP3 the strategy would be to improve efficiency and subsequently the performance. This strategy would enable both operations to enhance their overall efficiency performance and consequently the phase I overall efficiency and eco-efficiency performance.

	OP_1	OP_3	Phase I
Total efficiency index	0%	4%	2%
Real cost - Value prespective (€)	386,0 €	574,4 €	960,42 €
Target cost - Value prespective (€)	945,5 €	889,8 €	1 835,32 €
Cost effectiveness - Value prespective (%)	41%	65%	52%
Real environmental influence (Pt)	73,7 Pt	4,7 Pt	78,5 Pt
Target environmental influence (Pt)	1,5 Pt	1,7 Pt	3,2 Pt
Environmental Influence effectiveness (%)	2%	37%	4%
Real eco-efficiency	5,235	120,993	126,23
Target eco-efficiency	645,451	511,184	1156,63
Normalised Eco-Efficiency (%)	1%	24%	11%
Efficiency (%)	12%	19%	15%

Fig. 13. TEI for Operation 1 and Operation 3 in Phase I

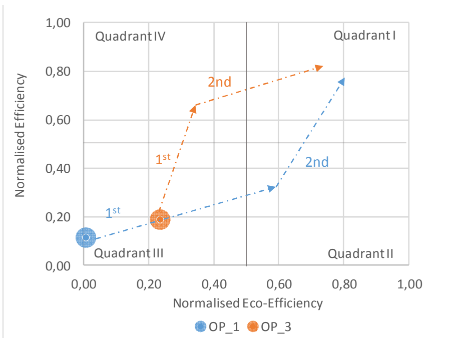

Fig. 14. Distribution of Efficiency versus Normalized Eco-Efficiency for Operation 1 and Operation 3 in Phase I

IV. Final Remarks

The Multi-Dimensional Design Assessment was developed as a multi-criteria approach to efficiency, eco-efficiency and costs assessment for a given design system in aeronautical industry production. Based on Lean Design-for-X approach, summed with other two methodologies, Multi-Layer Stream Mapping, for efficiency assessment based on Lean Principles, and ecoPROSYS, for eco-efficiency assessment, it was adapted to cover different dimensions at the design stage of a given production system, namely: resource efficiency; eco-efficiency; operational performance, and cost effectiveness. The Multi-Dimensional model was built considering a bottom-up approach, and in this aeronautical assembly system, each task is analysed within the assembly process in order to assess the performance of the several operations phases and then the respective built process.

The Multi-Dimensional Design Assessment approach enables the generation of "what if scenarios" to assess the real potential of the implementation of improvement actions. For instance, the trade-off analysis regarding the improvement of cost effectiveness and environmental impact could be performed, and also supported via the use of original graphical diagrams (quadrants) that compare the efficiency level versus the normalized eco-efficiency. A real example is given to demonstrate the approach, for the assembly of aircraft structure (Horizontal Tail Plane) where different results are presented and discussed for each dimension of analysis (efficiency, eco-efficiency, cost). Model limitations are mainly related with data quality and availability, with the need to clearly define and allocate the resource consumption within each assembly processes and tasks, since incorrect definitions and allocation of resource consumption will distort results and to misleading analysis. Additionally, manual parameterization of the model could be to costly and time consuming.

In order to overcome some of the limitations, and as future work, the model will be implement as a Software module, which is parametrized using the data within the PLM software, thus allowing to have all data centralized and enabling a swift implementation and deployment on the Multidimensional Design Model. Additionally, by using data form the PLM software, errors related with the allocation of resources to each assembly processes and tasks will be mitigated. The software application will also enable to have instantaneous trade-off analysis and what if scenarios regarding environmental impacts, efficiency and costs.

Finally, the Multi-Dimensional Design Assessment framework can be applicable in other industrial sectors, such as the automotive due to its generalization capability.

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