Lecture Notes in Mechanical Engineering

Caterina Rizzi · Francesca Campana · Michele Bici · Francesco Gherardini · Tommaso Ingrassia · Paolo Cicconi *Editors*

Design Tools and Methods in Industrial Engineering II

Proceedings of the Second International Conference on Design Tools and Methods in Industrial Engineering, ADM 2021, September 9–10, 2021, Rome, Italy

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Preface

The ADM International Conference, promoted by the Italian Association of Design Methods and Tools for Industrial Engineering (ADM), constitutes the biennial international conference organized in the years in which the JCM Conference (joint conference of ADM, INGEGRAF, and S.mart) is not held.

The ADM2021 International Conference, held with a blended formula in Rome, Italy, September 9–10, 2021, and hosted by Sapienza University, represents the opportunity to restart after the pandemic.

On behalf of ADM, I thank the Scientific Societies INGEGRAF and S.mart that have given a very important contribution.

I wish to thank all the members of the ADM board and all the members of the Scientific Council, in particular the Coordinator, Prof. Caterina Rizzi, for their availability, sensitivity, and efforts that made possible to organize the ADM2021 International Conference.

A special thanks to all the members of the scientific and the organizing committees, in particular to Professor Francesca Campana who has solved all the organizational problems.

Thanks a lot to all the authors and to all the international and Italian reviewers. Their activity has allowed the papers to reach such a high scientific level to be published in this prestigious book.

Finally, I thank all the ADM members. Their support has been fundamental for the organization of the ADM2021 International Conference.

Vincenzo Nigrelli
ADM President

Letter to the Authors

Dear Attendees and Authors,

It is a great honor and pleasure to welcome you to the International Conference ADM 2021 promoted by ADM, the Italian Association of Design Methods and Tools for Industrial Engineering, held, with a blended formula, in Rome, Italy, September 9–10, 2021. The conference is hosted by Sapienza University, a worldwide well-known university.

The conference aims at sharing knowledge, experience, and progress in the areas of design and manufacturing with links between industry and academia. It provides a forum for researchers, educators, and professional engineers to present and discuss their latest researches, results, major bottlenecks, and future trends.

Through the exchange of ideas, even virtually due to the pandemic, ADM 2021 is intended to facilitate the creation of multidisciplinary collaborations, new developments and discoveries for new product design and manufacture, health care, transportation, cultural heritage, and sustainability.

The conference offers the opportunity to the delegates to interact and understand how the application of emerging technologies impacts on critical engineering activities such as product design, manufacturing, management, and integration of information along the product life cycle.

This book collects 96 scientific papers across a wide range of session topics that cover a broad spectrum of themes including theoretical issues, methods, tools, processes, and case studies. The topics span from geometric modeling to virtual/augmented reality, human-related and user-centered design, integrated methods for system design, simulation, analysis and optimization, design for additive manufacturing, eco-design, engineering education, and many other subjects applied in different contexts, such as automotive, aerospace, cultural heritage, and health care.

We have also the privilege to host outstanding keynote speakers who will focus on related state-of-the-art technologies in some of main topics of the conference.

To conclude, I would like to thank all the authors for their valuable contribution to the book and each and every one of you for making ADM 2021 successful with your expertise, commitment and active engagement. Special thanks go to Conference Program Chair, Prof. Francesca Campana, and to the members of the organizing committee for their tremendous efforts for making this conference possible, especially during the pandemic.

You are warmly welcome to enjoy the conference and, who will be in presence, the wonderful Rome city.

Caterina Rizzi
ADM2021 Conference Chair

Introduction

This volume collects the proceedings of the ADM2021 International Conference, entitled "Design tools and methods in industrial engineering II," held in Rome (Italy) from September 9–10, 2021, Faculty of Civil and Industrial Engineering of Sapienza.

It is a great honor for me hosting the conference as Chair and coordinating the second edition of this International Conference, which took place for the first time in the University Campus of Modena in September 2019. ADM conference was conceived as the Italian venue to strengthen the network of international research and to meet our colleagues in Italy. The spirit of this venue is similar in conception to that inspiring the Joint Conference on Mechanics, Design Engineering and Advanced Manufacturing (JCM), organized by ADM (Italian Association of Design and Methods for Industrial Engineering) together with the Spanish members of INGEGRAF and the French members of S.mart.

The presence of 96 articles, coming from different European countries and the work of over 100 reviewers, demonstrates the activity of our research community, despite the problems related to the pandemic.

I wish to thank all the colleagues who have collaborated with me as Organizers: Michele Bici and Daniela Pilone of Sapienza, Paolo Cicconi of the University of Roma 3, Tommaso Ingrassia of the University of Palermo, and Francesco Gherardini of the University of Modena and Reggio Emilia to whom I deserve special thanks for having "passed the baton" to me in the conference organizational relay.

I wish to thank also all the colleagues who have supported us as Members of the Scientific Committee and as Reviewers and all Authors who gave their valuable contribution to the conference with their research. Likewise, I thank President of ADM Prof. Vincenzo Antonio Nigrelli and Prof. Caterina Rizzi, Coordinator of the Scientific Council of the ADM.

A further thank is due to Altair and the ASME Italian Section for their patronage, to the Sapienza institutions, the Faculty of Civil and Industrial Engineering and the Department of Mechanics and Aerospace, for hosting us. Last, but not least, the publisher Springer Nature, who honored us by publishing the proceedings of this second edition in the series "Lecture Notes in Mechanical Engineering."

With the hope that ADM2021 and the presence in Rome can also set the restart for new opportunities for social sharing and research.

Francesca Campana
ADM2021 Conference Program Chair

Organization

ADM2021 is organized by ADM—Italian Association of Design Methods and Tools for Industrial Engineering, in cooperation with Dipartimento di Ingegneria Meccanica e Aerospaziale of Sapienza Università di Roma, Italy.

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Geometric Modelling and Analysis

On the Geometrical Complexity Index as a Driver for Selecting the Production Technology

Alessandro Greco(✉), Pasquale Manco, and Salvatore Gerbino

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Abstract. Emerging production technologies, in particular Additive Manufacturing (AM), nowadays are extremely suitable for creating highly complex products, tending towards the concept of 'complexity for free', which is often associated with AM. However, there are no adequate guidelines to provide decision support for the correct selection of the most economically appropriate technology. Indeed, from literature it has been highlighted the need to develop a technology selection methodology based no longer on production volume but on product complexity. This paper investigates this need by presenting an approach to determine the geometrical (or shape) complexity index of a part, which, combined with the assembly complexity, represents the driver for helping to decide the best production technology (traditional or additive). The geometrical complexity index has been determined based on complexity judgments, provided by CAD modelling experts, for a sample of CAD models. In this way, it has been possible to define a preliminary complexity index model, strictly linked to the CAD model information. The results showed that the geometrical complexity metrics from the literature, if individually considered, are not comprehensive. However, a combination of them makes it possible to obtain an index that best reflects the subjective judgement of the experts. In addition, by combining the geometrical and assembly complexity with a cost analysis it is possible to obtain convenience zones for better selecting the production technology.

Keywords: Geometrical complexity · CAD · Survey · Technology selection

1 Introduction

In the era of the fourth industrial revolution, the technological innovation is closely linked to the increasing complexity of products available on the market. Identifying, analyzing and understanding complexity factors represent the first step to manage the complexity at a strategic level to improve company competitiveness. Providing a universal definition of complexity, to date, is still a difficult process because, unlike other physical quantities,

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complexity is not properly measurable. Therefore, further research is needed to make practical the concept of complexity.

The state of the art about complexity in science is considered multidimensional and it is explored from three points of view: (i) Design and Product Development Complexity, (ii) Manufacturing and Manufacturing System Complexity, (iii) Business and Marketing Complexity [1]. From an engineering point of view, the literature review on complexity can focus on three fundamental aspects: design, manufacturing and assembly.

Since the 1980s, several methodologies for evaluating technological complexity have been introduced. In the first decade of 1980s, the technique of expert systems was widespread, i.e. mathematical programs which, on the basis of input provided by operators, provided an index of complexity. Instead, since the 1990s, mathematics has been simplified, leaving the assessment of certain parameters to the subjective judgment of experts by means of questionnaires. In addition, there are also several more rigorous approaches based on objective system data, as described in the following section.

1.1 Geometrical or Shape Complexity

Complexity in design is generally related to the geometry of the part. In applications such as computer graphics and Finite Element Analysis, polygonal meshes are defined in terms of the geometry and connectivity of the nodes. The shape complexity measures how entrapped the polygon is. In addition to being closely associated with geometry, shape complexity is also associated with organizational and operational aspects of CAD software. Indeed, often it is also called CAD-complexity [2]. About CAD modelling, for each individual the complexity varies; for someone a task may be feasible, while for someone else it may be frustrating. Complexity is associated with the actual shape to be achieved in the project and derives from a strategic use of the functionalities provided by the CAD software. Contemporary CAD software, based on parametric associations, facilitates the creation of fully parameterized products. Thus, the complexity of the design activity is related to the complexity of the product, hence to the geometric complexity of the design.

The complexity of a component has implications in the design and especially in the production phase. In fact, in the mechanical field there is a need to produce increasingly complex and multi-functional parts, so the need for the development of a complexity model as in additive as in the traditional manufacturing is essential.

In literature there are several definitions about geometrical complexity and several metrics have been defined for an objective quantification of it. In particular, about objective metrics, Joshi and Ravi [3] proposed both *Sphere Ratio* (SR) and *Part Volume Ratio* (PVR) for quantifying the complexity. SR represents the ratio between the surface area of a sphere with the same volume of the part and the surface area of the part itself; PVR is the ratio between the volume of the part and the volume of its minimum *Bounding Box*. Lian et al. [4] defined the complexity as the ratio between the volume of the part and the volume of its convex envelope. They talk about *Convex Envelope Complexity* (CEC) and this is the most used metric. Always linked to geometric characteristics, Chougule and Ravi [5] quantified the complexity by proposing the *Cube Ratio* (CR), defined as the ratio between the surface area of a cube with the same volume of the part and the surface area of the part itself. Table 1 describes the mathematical definition of these metrics.

Table 1. Geometrical complexity metrics.

Metrics	Equation	Parameter
Sphere Ratio - SR	$SR = 1–(A_{sphere}/A_{part})$	• A_{sphere}: surface area of sphere* • A_{part}: surface area of part
Part Volume Ratio -PVR	$PVR = 1–(V_{part}/V_{BBox})$	• V_{part}: part volume • V_{BBox}: part's bounding box volume
Convex Envelope Complexity - CEC	$CEC = 1–(V_{part}/V_{CE})$	• V_{part}: part volume • V_{CE}: part's convex envelope volume
Cube Ratio – CR	$CR = 1–(A_{cube}/A_{part})$	• A_{cube}: surface area of cube* • A_{part}: surface area of part

(*) cube and sphere have the same part's volume.

Other metrics, proposed by literature, appear to be linked also to other information characterizing a CAD model, not always related to geometrical properties. Qamar et al. [6] estimate omplexity as function of the ratio of the perimeter of a cross-sectional area to be extruded and the round bar perimeter having same cross-sectional area. Bodein et al. [7] suggest to examine the complexity based on the *number of surface* composing a part. Lastly, Valentan et al. [8] associate the complexity to the number of triangle required for representing an object in a *.stl* file.

From the literature review, it is possible to point out that: i) none of these metrics, taken individually, are exhaustive in describing geometrical complexity; ii) only a few studies tried to compare them with each other, but based on small samples of models [9, 10]; iii) probably a weighted combination of these metrics could provide more comprehensive results than those provided by individual metrics.

1.2 Aim and Outline of the Paper

In continuity with a previous work [10], in which the geometrical complexity metrics described in Table 1 have been compared and correlated with each other, this paper is aimed at filling some gaps of literature by providing a more general complexity metric, based on a linear combination of the metrics described above. Each metric has been correlated against the CAD expert user judgments, pointed out from a survey.

In the next section, the methodology is described. Then, a case study is presented, followed by results and discussion. Finally, conclusions and future work are detailed.

2 Method

The heuristic approach, which uses metrics based on knowledge and personal experience, is easy to apply but the actual complexity metrics remain subjective. W. Elmaraghy and Urbanic [11] present a methodology to assess product and process complexity by considering a set of complexity indices. Fera and Macchiaroli [12] propose a revisitation of the methodology in [11], and introduce a new formula (Eq. 1), which considers the contribution of geometrical complexity, evaluated as: i) Convex Envelop Complexity (CEC), as defined in Table 1; ii) Operational Complexity (OC), which depends on the number and the type of operations necessary to produce the part; iii) the variety of information (IV) and the information entropy (H), which are related to the number, type and diversity of features that have to be manufactured. M is a normalizing factor.

$$PC = \frac{1}{M}(IV + CEC + OC) * H \tag{1}$$

As reported in the Sect. 1.1, the literature proposes different approaches for evaluating the geometrical complexity. So, the purpose is to introduce a complexity index able to account both objective metrics and expert judgement.

The new geometrical complexity contribution, substituted in Eq. 1, provides an overall complexity index that better addresses the selection of the appropriate production technology.

Figure 1 shows the adopted methodological framework. It points out the focus of the present article which is related to the geometrical complexity.

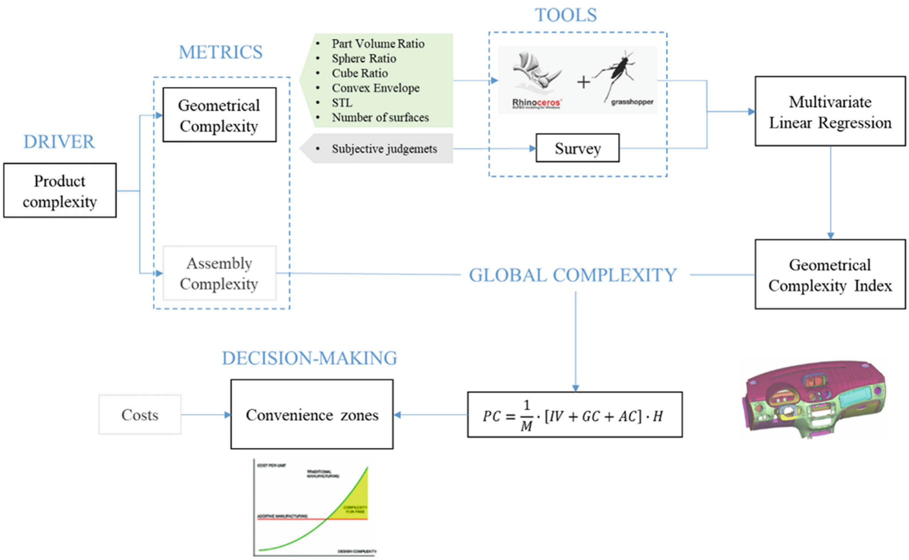

Fig. 1. Methodological framework.

As mentioned above, the driver for technology selection is the Product Complexity (PC), which is defined, in the case of manufacturing field, by both geometric complexity and assembly complexity. The latter, is obtained by using the information contained in the Standard Operating Procedures (SOPs). The measuring procedure as explained in Samy & ElMaraghy's work [13] has been applied. Considerations about handling and insertion attributes of each component have been made to measure the weighted average values of the part assembly complexity factors (C_{part}), according to the following equation:

$$C_{part} = \frac{C_h \sum_1^J C_{h,j} + C_i \sum_1^K C_{i,k}}{\sum_1^J C_{h,j} + \sum_1^K C_{i,k}} \in [0; 1] \tag{2}$$

where $C_{h,j}$ (j = 1,..,J) and $C_{i,k}$ (k = 1,..,K) are respectively the values of relative handling and insertion complexity factors, reported in [13]. The value J and K are the number of the considered attributes. C_h and C_i take on values between 0 and 1. They are respectively the average handling and insertion complexity factor of the part.

About the geometrical complexity, as described in Sect. 1.1, several authors proposed a series of metrics to define it in an objective manner (Table 1). Instead, subjective metrics are based on complexity judgments attributed by experts in CAD modelling, who have a broader vision of the modelling world and who know how to recognize the difficulties that may be encountered during the part creation process. The complexity judgement is attributed following a simple psychometric measurement technique developed by Rensis Likert [14]. Typically, the range of ratings goes from 1 to 5, where 1 stands for "very simple" and 5 stands for "very complex".

In order to evaluate the geometrical complexity metrics, the tools used for evaluating objective and subjective metrics are the plug-in Grasshopper for Rhinoceros® and a survey respectively. In Grasshopper, by means of blocks, it is possible to build real workflows in a Canvas that, starting from the CAD model, provides all the parameters needed to evaluate the objective metrics.

The survey for the acquisition of subjective metrics involves CAD modelling experts (both from industry and academy). Each interlocutor is invited to express an opinion, based on Likert scale, on CAD models, considering some evaluation parameters such as modelling strategies, symmetries, patterns, features, linearity and curvature of surfaces, etc.

Once the objective and subjective metrics, related to a sample of CAD models, have been obtained, an analytical relationship between the "perceived" complexity of a component and its objective characteristics can be obtained by means of multivariate linear regression, by considering the subjective judgements as depended variable and the objective metrics as independent variables.

The overall complexity index (PC), considering the obtained Geometric Complexity (GC) index and the Assembly Complexity (AC), based on Eq. 1, is done by the following equation:

$$PC = \frac{1}{M}(IV + GC + AC) * H \tag{3}$$

The decision-making process involves the complexity of the product and the cost analysis related to the production technology (additive or traditional). So, it allows the identification of areas of convenience for selecting the appropriate technology.

3 Case Study

This section is aimed at demonstrating the effectiveness of the framework proposed in Fig. 1. The case study investigates the technology selection for the production of 26