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Received 27 January 2021
Revised 30 April 2021
Accepted 29 May 2021

Visualizing knowledge for decision-making in Lean Production Development settings. Insights from the automotive industry

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Abstract

Purpose – The paper focuses on how knowledge visualization supports the development of a particular multiobjective decision-making problem as a portfolio optimization problem in the context of interorganizational collaboration between universities and a large automotive company. This paper fits with the emergent knowledge visualization literature because it helps to explain decision-making related to the development of a multiobjective optimization model in Lean Product Development settings. We investigate how using *ad hoc* visual tools supports knowledge translation and knowledge sharing, enhancing managerial judgment and decision-making.

Design/methodology/approach – The empirical case in this study concerns the setting up of a multiobjective decision-making model as a portfolio optimization problem to analyze and select alternatives for upgrading the lean production process quality at an FCA plant.

The authors would like to thank the guest editors and the two anonymous reviewers for their generous and encouraging feedback. The authors would also like to thank the quality team at the Pratola Serra Plant – FCA, Italy, EMEA Region, coordinated by the Quality Manager, Giuseppe Spina for invaluable support received at each stage of the research. Special thanks go to Prof. Massimo Squillante for his precious work of scientific coordination and stimulus in undertaking innovative study trajectories.

Findings – The study shows how knowledge visualization and the associated tools work to enable knowledge translation and knowledge sharing, supporting decision-making. The empirical findings show why and how knowledge visualization can be used to foster knowledge translation and sharing among individuals and from individuals to groups. Knowledge visualization is understood as both a collective and interactional process and a systematic approach where different players translate their expertise, share a framework and develop common ground to support decision-making.

Originality/value – From a theoretical perspective, the paper expands the understanding of knowledge visualization as a system of practices that support the development of a multiobjective decision-making method. From an empirical point of view, our results may be useful to other firms in the automotive industry and for academics wishing to develop applied research on portfolio optimization.

Keywords Decision support systems, Knowledge visualization, Knowledge translation, Knowledge sharing, Decision-making, Decision analysis

Paper type Research paper

1. Introduction

Lean Production Development (LPD) can be described as the application of lean principles to product development. LPD settings typically require decision-makers to try to achieve multiple conflicting objectives for production processes at the plant level (Gurumurthy and Kodali, 2008; Jaiswal *et al.*, 2021; Stoycheva *et al.*, 2018). LPD relies on a set of engineering and work organization principles and techniques, many of which were first popularized by Toyota (Canonico *et al.*, 2020). These are designed to achieve shorter lead times, reduced costs and higher quality than traditional product development. According to Dombrowski *et al.* (2012), the management of knowledge plays a critical role in LPD settings: a lean production system requires the creation and distribution of information, and therefore, the identification, acquisition, development, transfer, application and preservation of knowledge.

Multiobjective optimization decision-making is a field of operational research based on the application of a logical preference model (Greco *et al.*, 2008) built with the continuous interaction of the decision-maker (Sarnataro *et al.*, 2021). In LPD settings, this approach provides decision-makers with the information needed to interpret data on production processes (Canonico *et al.*, 2018). The complex formulation of decision support systems such as the multiobjective optimization model means they need to use graphs to communicate with decision-makers to refine the model and improve the results (da Silva *et al.*, 2017). Practitioners often do not clearly perceive the practical implication of multiobjective methods, given the interpretation difficulties for nonexperts. There is, therefore, a growing need to make use of knowledge visualization to overcome interpretative biases of decision-makers.

This paper fits with the emergent knowledge visualization literature (Eppler and Pfister, 2014; Eppler and Platts, 2009; Gavrilova *et al.*, 2017a) because it helps to explain decision-making related to the development of a multiobjective optimization model in LPD settings. We investigate how using *ad hoc* visual tools supports knowledge translation and knowledge sharing, enhancing managerial judgment and decision-making (Eppler, 2013; Eppler and Burkhard, 2007). The paper focuses on how knowledge visualization supports the development of a particular multiobjective decision-making problem as a portfolio optimization problem in the context of interorganizational collaboration between universities and a large automotive company.

Our research questions were: how does knowledge visualization support the development of a portfolio optimization problem in an LPD setting? What are the features of knowledge visualization processes in terms of knowledge translation and sharing among researchers and plant managers? We analyzed material collected within Fiat-Chrysler Automotive (FCA), a multibrand auto manufacturer with a product range covering several different market segments. Two authors were involved in the collaboration project and participated in all development processes.

The next section of this article analyses the specific features of the relationship between decision-making processes and knowledge visualization in an LPD setting and examines the concept of knowledge visualization as a process. The article then describes the methodology used for the empirical analysis, the findings and conclusions.

2. Decision-making and knowledge visualization

Over recent decades, data analysis for decision-making in industrial settings, close to the assembly line, has shifted from the IT department to business units and operations. It now uses more intuitive tools and more effective visual representations. Knowledge visualization tools can provide useful support to facilitate decision-making processes. Data conveyed to decision-makers are often most useful if converted into values that then acquire meaning through formal rules and subsequent analysis. When confronted with visualization of particular forms of knowledge, decision-makers may rely on being able to understand discontinuities, things that stand out, and variations in color and shape, or to recognize patterns using visual cues (Kosslyn, 1994). The typical overload from the volume of complex data required to read a phenomenon from different angles may be overcome by presenting knowledge visually, supporting associative reasoning (Lurie and Mason, 2007). Visual knowledge enables us to move from the saying that "a picture is worth a thousand words" to recognize that "a picture is worth a thousand rows [of a matrix]" (Lurie and Mason, 2007, p. 160).

There are now tools to help decision-makers reduce large data sets to simple visuals. Following Berinato (2016), management visualizations of complex methods can be simple auto-explanatory representations with a declarative statement. They clearly communicate a single idea backed by data. These visualizations are a design challenge not because of their structure but the effect they need to create. Visualization tools range from bar graphs to virtual representation of reality. Early work extending visual representation beyond simple charts and graphs found that graphic displays enabled managers to "make use of the uniquely human ability to recognize meaningful patterns in the data" and to see "patterns in data that would never have been picked up with standard statistical methods" (Kolata, 1982, p. 919). Visualization tools are an intermediate step in converting data into insights (Green, 1998). Data characteristics such as dimensionality (the number of both cases and variables), scale (categorical, ordinal and metric), and cardinality affect the selection of tools. Visualization techniques rely on dimensions such as color, size, shape, texture and visual orientation, which can affect the insights derived from the data. Visualization tools, therefore, have implications for understanding the decision-making process and outcome and the potential bias generated.

In LPD, the use of visual controls is common on the shop floor and supports other management functions such as development processes (Aas and Alaassar, 2018). Visualization may be extremely helpful in LPD, especially "any communication device used in the work environment that tells us at a glance how work should be done and whether it is deviating from the standard" (Liker, 2004, p. 169).

When setting the analysis of knowledge visualization in LPD environments, it may be useful to explore the match between the typologies of both decision-making and knowledge visualization needed. Decision-making models can be studied using two perspectives, prescriptive and descriptive models (Bazerman and Moore, 2013). Prescriptive models use a mathematical approach to generate decision models that help decision-makers to make the best possible decisions (they prescribe how decisions should be made). For instance, Bazerman *et al.* (1998) put forward a six-stage decision-making process using a prescriptive approach with a rational model that achieves the best results. The stages were: defining the problem, assessing the criteria, weighting the criteria, generating alternatives, rating alternatives against criteria and deriving the optimal decision. Descriptive models are concerned with how decision-makers make decisions. One of the basic ideas in the literature is the well-known concept of bounded rationality, introduced by Herbert Simon. The underlying idea is that rational behavior has constraints. Even with the resources and cognitive abilities to make the best possible decision (as proposed in prescriptive models), rational decision-makers will discount the potential lack of information and human mind boundaries that prevent them from making the optimal decision. To overcome these challenges, heuristics and bias mechanisms can help redirect decision-makers' judgments. Graphic displays may help decision-makers to see patterns in data that are more difficult to detect through statistical methods, improving decisions (Lurie and Mason, 2007). However, this can also make the process more complex and highlight irrelevant data (Lurie and Mason, 2007).

To sum up, visualization can help to support decision-making processes, but it is important to understand its role in terms of knowledge. Visualization tools can be interpreted as knowledge enablers: they could influence knowledge processes such as sharing, integrating and translating.

3. The theory of knowledge visualization

The concept of knowledge visualization has been recently associated with the contribution of the so-called "St Gallen School" (Gavrilova *et al.*, 2017b). It is also connected with visualization management and a long tradition in the visual communication field. Many typical managerial concepts are theoretically close to knowledge visualization. Eppler (2013) noted that it is possible to consider at least 20 different concepts contributing to knowledge visualization from different disciplines. One of the most common in the managerial tradition is the concept of the boundary object. This richness is related to the attempt to make knowledge visualization more theoretical and is coherent with the ideas expressed by Gavrilova *et al.* (2017b), who suggested that knowledge visualization research is in the theory construction phase.

The first issue to consider is the need for a clear definition of the concept, highlighting the differences and similarities with other topics. Early approaches to classification did not distinguish between data and knowledge visualization (Gavrilova *et al.*, 2017b, p. 12). An important contribution from Eppler and colleagues was to clarify knowledge visualization and its main characteristics. This suggested that knowledge visualization could be considered as a process where those involved try to facilitate typical knowledge management processes such as knowledge sharing, knowledge translation and knowledge integration.

This idea looks coherent with the traditional classification within the knowledge management field, in which knowledge is typically associated with two different perspectives. Swan *et al.* (1999) separated knowledge management into two contrasting models: the cognitive network model and the community-networking model. In the first approach, knowledge is assimilated to any other resource that management may control (individual dimension of knowledge). In the second, knowledge is found within social relationships (collective dimension of knowledge). The two models can be considered as alternative ways of viewing both the management of knowledge and organizations themselves. Both models are rooted in other disciplines. The cognitive network model is linked to cognitive psychology, which considers that the mind acts as a function of the brain to establish representations of the outside world (Stacey, 2001). The community-networking model draws on different theoretical contributions, which have gradually flowed into sociology (Berger and Luckmann, 1966). It suggests the social side of human existence is how people build and interpret reality. A fundamental difference between the two is in the definition itself, especially the evolution from the use of the term "network" as a substantive entity (a well-defined object within time and space constraints) to the term "networking," showing an "in progress" dynamic attitude. This therefore moves the concept of knowledge from a resource to a process.

The St Gallen perspective sees knowledge visualization as related to the idea of a facilitator activating reactions in group dynamics. This paper uses Eppler's definition (2013, p. 4):

> KV [Knowledge visualization] designates all (interactive) graphic means that can be used to develop or convey insights, experiences, methods, or skills [6, 7]. This definition implies that the realm of KV is not limited to computer-based images and that the main purpose of KV is to support the (inherently social) processes of creating and sharing knowledge with others.

In a broader sense, creating and sharing knowledge uses classical labels such as knowledge integration or knowledge translation. Knowledge visualization should facilitate conversations among a group (Eppler, 2013, p. 5).

This definition of knowledge visualization was proposed very early on (see, for example, the seminal paper by Eppler and Burkhard (2007), which introduced this new "discipline"). However, the recent evolution of the concept has focused on the dynamic and processual view or the idea of moving from knowledge visualization to visualizing knowledge. Eppler (2013, p. 3) noted: "The objective of the current chapter is to make this rich legacy of the knowledge domain field visible and use it to inform the practice of visualizing knowledge." The term *practice* is a reminder of the social construction tradition, as is the use of the *ing*-form. Knowledge visualization is not a static element but a living process involving people, actions, contexts and relations. In a broader sense, creating and sharing knowledge uses classical labels such as knowledge integration or knowledge translation and "has to support the (group) process of knowledge integration among various people" (Eppler, 2013, p. 5). The knowledge translation perspective is related to the adoption of the boundary object concept, and Eppler (2013, p. 9) stated: "They [boundary objects] have different meanings in different social or professional contexts, but their structure is common enough to more than one professional community to make them recognizable means of translation." Some scholars have adopted the concept of knowledge translation (Secundo *et al.*, 2019, p. 274) to observe that "when knowledge is transferred across very diverse contexts (e.g. from academia to industry), knowledge needs to be translated to still be interesting and relevant."

At a general level, it is possible to argue that knowledge visualization is still in an embryonic stage as a managerial theory, notwithstanding recent contributions discussed by Gavrilova *et al.* (2017b). It lacks a relationship with the concept of decision-making, apart from a few exceptions. Eppler and Platts (2009) discussed the role of knowledge visualization in a strategic planning process, including the adoption of different visualization tools at different steps of the process. Strategic planning is a complex process with several stages and decisions and provides emotional, cognitive and social challenges. The authors offered important reflections and tips about selecting the right visualization tool at each step. Unfortunately, there is no clear reference to Eppler's concept of knowledge visualization as a process.

This paper investigates knowledge visualization as a process supporting knowledge sharing in a decision-making process. Our goal was to verify how visualization tools are adopted in the process and the advantages (or disadvantages) associated and to understand what happens in the time between sharing the visualization tool and the decision being made.

4. Methodology

The empirical case in this study concerns the setting up of a multiobjective decision-making model as a portfolio optimization problem to analyze and select alternatives for upgrading the lean production process quality at an FCA plant. The case study origins sit within an innovative industrial Ph.D. project, launched in April 2018. It involved a research group consisting of a Ph.D. student, two professors from the University of Sannio, two professors from foreign universities, and the quality team at the FCA plant in Pratola Serra, Avellino, Italy, the project partner. This study used empirical material collected at the plant. In recent years, this plant has achieved several certifications and awards but has also experienced some problems and important organizational development in LPD processes.

The construction of portfolio optimization problem models provides for the direct and continuous involvement of decision-makers to simplify the collection of information for the analyst (Sarnataro *et al.*, 2021), and to help decision-makers understand the decision problem better. This generates a continuous and constructive exchange of knowledge between groups. In constructing the model, a qualitative approach was used for the selection, definition and representation of the study phenomena, with the direct involvement of the company management (Esposito *et al.*, 2019).

Three data collection techniques were used: documentary analysis, participant observation and semi-structured interviews. The documentary analysis made it possible to understand how the errors are made by workers in the engine assembly phase. This enabled an understanding of how the management makes decisions to deal with errors. Participant observation was used to explore the organizational controlled relationship and management controlled reports, to define the most suitable mathematical approach to the problem. During fieldwork, one of the authors spent two days a week at the plant for three months. Having free access to the plant premises, she was able to make both formal and informal contacts and become relatively familiar with the management. Finally, in-depth interviews with the management of FCA were the main source of data for this study (Canonico *et al.*, 2017). Semi-structured interviews were conducted with the World Class Manufacturing Plant coordinator, two manufacturing engineering managers (quality team members), the plant quality manager and the Pratola Serra plant manager. The interviews were based on an open, wide-ranging protocol (Czarniawska, 2004) provided one week before the first interview. The protocol aimed to stimulate interviewees' interest in this participative research process and promote a narrative approach, which was considered crucial for the success of the interviews. The questionnaire included questions about:

(1) The overall development of the multiobjective optimization decision-making model as a portfolio optimization problem (for example, how many phases/steps were used for the process? What were the working methods and critical points of each phase?);

(2) Organizational practices within the cross-boundary team (What were the main coordination mechanisms used among academics and engineers? What actually happened? Can you provide an example of a problem that you solved through visualization tools?);

(3) Knowledge visualization mechanisms and practices used (How useful were visualization tools at different stages of the decision-making process? How were those visual tools actually used? How and why were visualization tools effective in helping you understand the mathematical approach and facilitating decision-making?).

Each interview was conducted by two authors of this paper to reduce interviewer bias (such as first-impression error, nonverbal influences or negative emphasis). The interviews lasted between 90 and 180 min. At the end of each interview, the two authors reported, shared and discussed the outcomes. We adopted Ricoeur's (1986) approach of viewing those involved as readers confronted by a text. They were considered to be actively involved in creating the language of the context surrounding them, consisting of narrative phenomena.

5. Empirical study

We analyzed the knowledge visualization techniques used in the construction of the multiobjective optimization mathematical approach (Barbati *et al.*, 2018b; Fattoruso *et al.*, 2021). Multiobjective optimization takes into account the subjective preferences of a decision-maker to find one or more solutions to a decision problem with multiple objectives and constraints (Barbati *et al.*, 2018b). Our case described a portfolio optimization problem (Fattoruso *et al.*, 2021) with different levels of risks and financial resources (Ghasemzadeh and Archer, 2000). An elaborate mathematical approach was developed to solve this decision-making problem, which could be very difficult for managers to understand. Knowledge visualization techniques were used to simplify the interpretation of the mathematical formulation and the logical constructs that support the model. Our goal was not to explain the mathematical approach of the portfolio problem used in FCA but to analyze whether and how knowledge visualization activates different dynamics to support decision-makers.

For fitting into our framework, the analysis of the activities was grouped into four steps (see Figure 1):

(1) Definition and analysis of the decision problem;

(2) Choice and explanation of portfolio optimization problem using *ad hoc* visualization tools;

(3) Visualization tools to help the decision-maker to choose between alternatives;

(4) Sharing the decision moment and common reflection for the final choice.

Every step in Figure 1 was associated with some of the phases in the decision process.

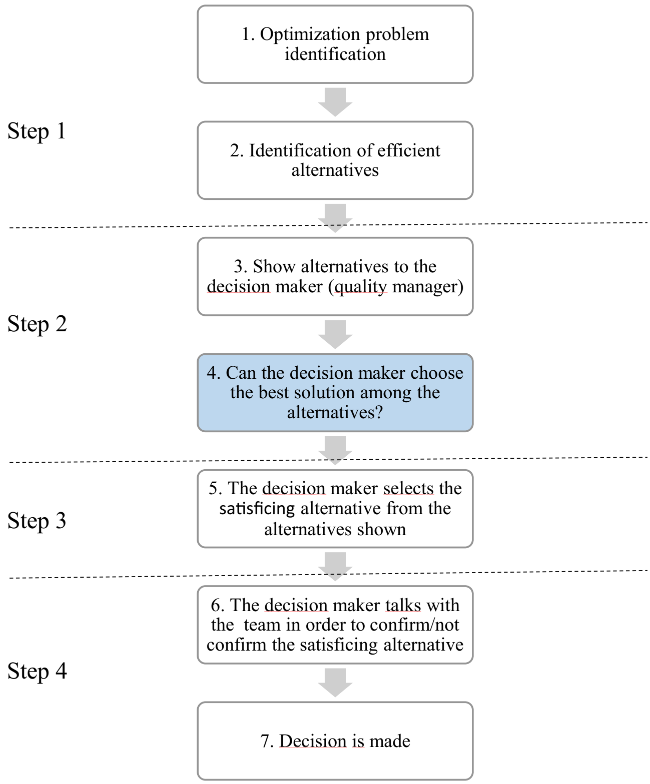

Figure 1.
The multiobjective optimization steps and decision-making process

Step 1 – Definition and analysis of the decision problem

The first step was focused on defining the decision problem with the Quality Manager. The first interaction was made by the Ph.D. student and two professors from the University of Sannio in an unstructured interview. In the interview, the focus of the decision-making problem that emerged revolved around the responsibility to ensure the quality and conformity of products, and therefore, the ability to detect defects generated in the production system and prevent defective products from entering the market. The phenomenon was studied by analyzing the history of the production process to identify the main cause of defects and adopt countermeasures to avoid their generation, and therefore, the need to intercept them. The main goal of the Quality Manager was to identify the critical points of the processes where errors occurred to prioritize action. During the interview, identifying the critical points of the processes in the company was established as the main objective of the decision-making problem. The goal was to identify a set of processes to be resolved in order of severity, based on the financial resources allocated by the company to improve processes.

Step 2 – Choice and explanation of portfolio optimization problem using *ad hoc* visualization tools

Following the discussion with the Quality Manager, the research group explored the best mathematical approach to support the management in identifying the critical points in processes. This required a multiobjective portfolio problem, which provides for the definition of an objective and constraints and the construction of portfolios. It is not always possible to select all processes at once because of constraints, so the goal was to select as many processes as possible, starting with the most severe. Over time, the manifestation of errors within processes is variable and can exceed the financial resources set aside by the company to resolve them. One of the constraints considered in the construction of the model was, therefore, the availability of financial resources. The goal was to assign a severity level to each process in the plant and build a portfolio of processes with the availability of financial resources as a constraint. We considered three different levels of availability: more than 50%, 50% and less than 50% of the total resources needed to solve all errors identified.

The optimization methods alternated between phases of calculation, where multiobjective optimization problems were solved, and dialogue with the decision-maker about preferences. Figure 1 shows the decision-making process (Greco *et al.*, 2008). The knowledge visualization process follows the vertical line, from phase three ("Show alternatives to the decision-maker" to phase seven ("Decision is made") – i.e. from step 2 to step 4.

The crucial point of the decision-making process is point 4 of Figure 1. When the alternatives were presented to the decision-maker (quality manager), he identified the satisficing alternative (point 5, Figure 1). He then met the quality team and plant manager to discuss his choice and confirm or modify it before making the final decision (points 6 and 7, Figure 1).

The mathematical approaches used were particularly complex Riesz spaces or all-groups (Cavallo, 2020; Cavallo and D'Apuzzo, 2015; Cavallo *et al.*, 2012, 2019a, b), which are difficult for nonexperts to understand. *Ad hoc* visualization tools were created to help the decision-maker to understand the mathematical approach and to simplify the choice between alternatives. For the multiobjective portfolio decision model, the definition of reference levels was envisaged to identify when a process could be considered optimal, tolerable and not tolerable based on the number and severity of errors. The research group, therefore, created *ad hoc* visualization tools to help the quality manager understand how the model worked and the reference levels that determined the critical points of the processes (see Appendix).

Figure 2 was used to show the quality manager that the critical points of the processes were classified by identifying reference levels of the number and severity of errors. Green

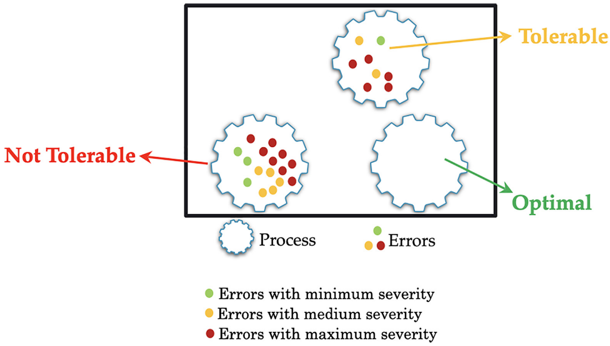

Figure 2.
Visualization tool for the critical points of the processes

errors are not very significant, and yellow errors had medium severity and red maximum severity. We could therefore use a questionnaire to identify two types of process, tolerable and optimal, and for each one, identify the number of errors with minimum, medium and maximum severity.

Once the reference levels for the critical points of the processes were defined, the method involved the construction of portfolios of sets of processes to be resolved (Barbati *et al.*, 2018a, b), depending on the financial resources available.

Figure 3 explained to the quality manager that portfolios were built using optimization methods that considered the composition of the critical points of the processes and identified the highest priority processes. We explained that this method also enabled prospective analysis, with different levels of availability of financial resources (more than 50%, 50% and less than 50% of the total required to solve all errors identified). This allowed the decision-maker to choose between alternatives.

Step 3 – Visualization tools to help the decision-maker choose between alternatives

The most important moment in the construction of multiobjective methods is choosing the best alternative (point 4 of Figure 1). The decision-maker has a crucial role, and it was not clear whether they would be able to identify the alternative that best meets the needs of the company.

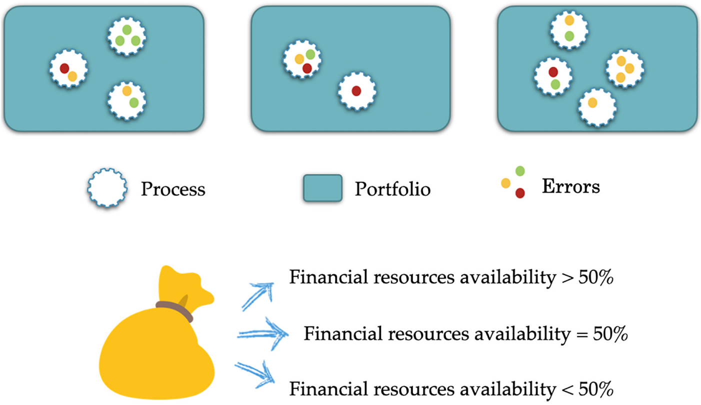

Figure 3.
Visualization tool: portfolio for the critical points of the processes

Portfolio optimization problems have the great advantage of being built with continuous interaction with decision-makers to provide a continuous exchange of information and knowledge among the people involved in the choice (Sarnataro *et al.*, 2021). It is, therefore, essential that the method is understood and that it can then be used and integrated into the company. In the presentation of the alternatives, which in our case were the portfolios of critical points of the processes, we used tables to summarize data for the initial comparison. However, the tables were difficult to read, and the quality manager had difficulty identifying the best alternative. He requested a simpler representation of these data using tools that would help him to compare the number of errors present for the critical points of the processes in a more intuitive way. Figure 4 shows an example of the tables presented to the decision-maker. It shows the composition of the portfolios with 50% of financial resources available.

To help the quality manager read the data about the critical points in the processes, we decided to use another visualization tool to show the alternatives and simplify the selection process. We chose a histogram because this allowed us to show the minimum, medium and maximum errors in the optimal and tolerable processes side by side, making them more easily comparable. The histogram shows the number of errors on the abscissa axis and the errors in order of severity (minimum, medium and maximum), for tolerable and optimal processes, on the ordinate axis. To make the histogram even clearer, we showed the optimal process bar in green and the tolerable process bar in yellow.

Figure 5 shows an example of the representation of the alternatives using a financial resources availability of 50%. After the second presentation of the alternatives using the histogram, the quality manager commented:

> Viewing alternatives with histograms is more intuitive and easier to share with the quality team and team leaders working on the production lines. [. . .] The choice is more immediate and more acceptable.

The complexity problem also emerged when showing the composition of the critical points of the processes within each portfolio. The quality manager was originally given a table in which the absence of the process was marked with an “A” and its presence with a “P.” However, he found it was difficult to develop an intuitive picture of the processes present in the various portfolios because the analysis was so complex. We, therefore, showed the composition of the portfolios using a horizontal bar histogram with the portfolios shown in different colors. The decision-maker again found this was more intuitive and enabled him to understand the processes that were in the different portfolios, providing a complete picture to help him to choose the best alternative. An example of the tabular representation and the horizontal bar histogram is shown in Figure 6.

At the end of the development of the decision-making problem, the managers involved were interviewed to understand which of the knowledge visualization tools had been most useful and interesting for the decision support system in the company. Those involved in the decision process said that the visualization tools were useful for understanding and assimilating the mathematical approach. The change of visualization tools was also useful in simplifying the choice of the best alternative. The quality manager commented:

	Tolerable			Optimal		
	Maximum	Medium	Minimum	Maximum	Medium	Minimum
Portfolio A	3	4	2	1	2	1
Portfolio B	3	7	2	1	3	0
Portfolio C	2	4	2	0	1	2
Portfolio D	3	7	1	1	4	1

Figure 4.
Tabular representation of the process portfolios

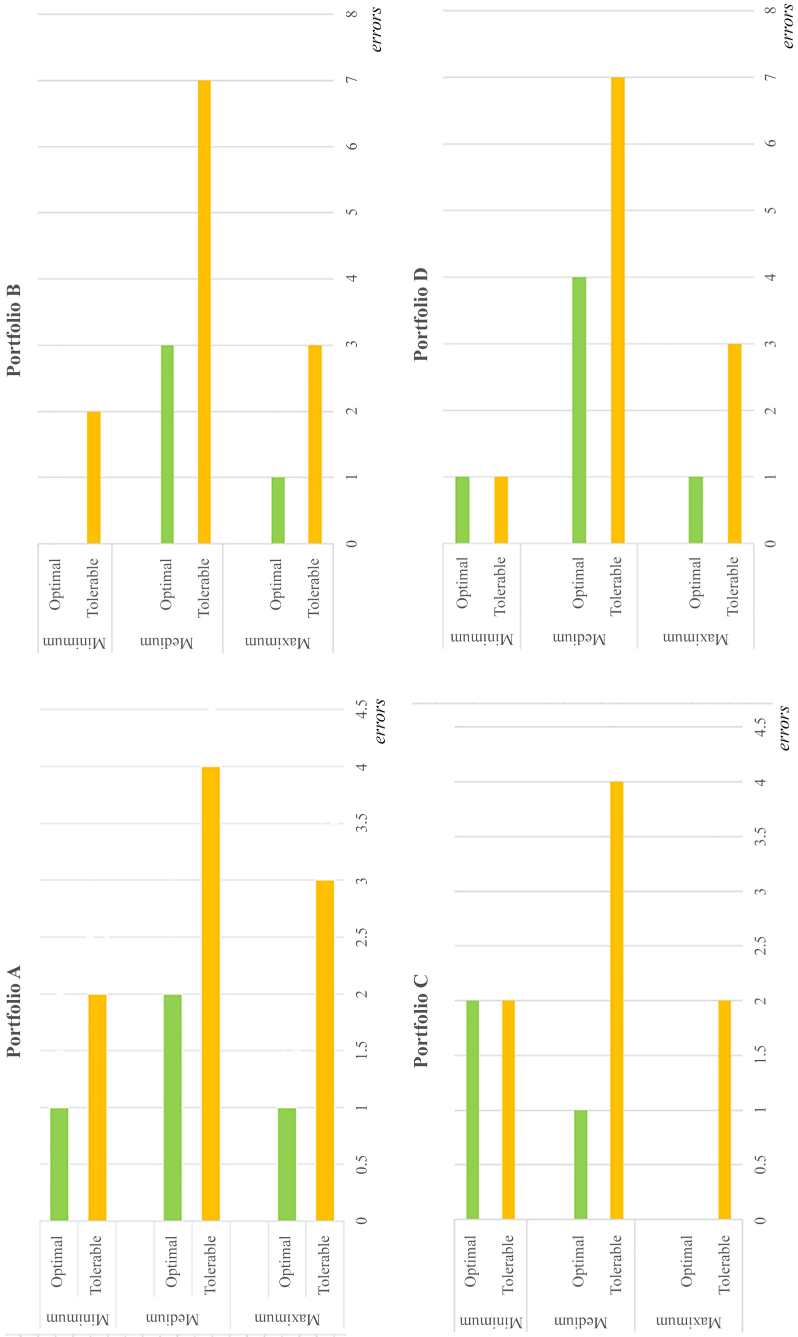

Figure 5.
Histogram showing process portfolios with 50% of required financial resources available

Critical Points of the Processes (CPP)	Portfolio A	Portfolio B	Portfolio C	Portfolio D
CPP 1	A	A	A	P
CPP 2	P	A	A	P
CPP 3	P	P	P	P
CPP 4	P	A	A	P
CPP 5	P	P	P	A
CPP 6	A	P	P	P
CPP 7	A	A	P	A
CPP 8	A	P	A	P
CPP 9	P	P	A	A
CPP 10	P	P	P	P

Before

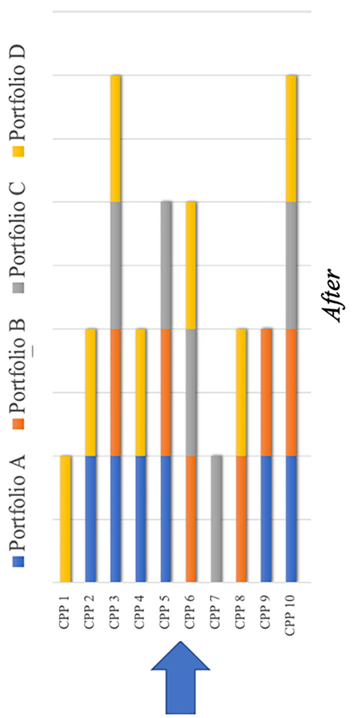

Figure 6.
Tabular representation vs horizontal bar histogram representation for 50% of financial resources available

> The visualization of technical data increased my awareness of the problems. The use of pictures, graphs and colors makes it possible to grasp complex relationships between many different factors very quickly …. Visualization helped to support fruitful communication and decision-making processes.

Step 4 – Sharing the decision moment and common reflection for the final choice

The quality manager shared the satisfying alternative with the rest of the team. There was a moment of sharing and reflection with the quality team and the plant manager to reach a shared choice. This operation was carried out to understand if further decisional constraints were necessary to solve the decision problem or if the alternative identified could be confirmed. The alternatives were shown using a PowerPoint presentation, first in tabular form and then with histograms to make it easier for everyone to understand. Following the presentation, the people involved talked about both the best alternative and the effectiveness of the visualization tools. The final choice (the alternative initially selected by the quality manager) was reached by identifying the portfolio considered best of the various alternatives. The plant manager commented:

> Visualization tools concretely support the quality team in the selection process [. . .]. The quality manager has the ability to quickly and effectively illustrate alternatives to his work team and thus reach a shared choice.

6. Discussion

By using the frame of knowledge visualization introduced earlier, this section discusses the concept as a complex and dynamic process (Figure 7) able to support decision-making in an LPD setting (Eden and Ackermann, 1998; Eppler, 2013; Eppler and Platts, 2009). The decision-making context is coherent with the prescriptive approach (Bazerman and Moore, 2013), where the role of knowledge is particularly relevant in the generation and selection of the alternatives defined by the model. Our study focused on the final part of the decision-making process (from point 4 in Figure 1), which needed considerable dialogue between academics and managers. The context in which the decision-making model was developed was characterized by two very specific domains of knowledge that, in line with Grant's approach (1996), needed a very low degree of integration: it is an economical choice when specialists have different backgrounds. Grant (1996, p. 380) argued:

> Generally speaking, the wider the scope of knowledge being integrated (and, hence, the greater the diversity of the individuals involved), the lower is the level of common knowledge, and the more inefficient the communication and integration of knowledge.

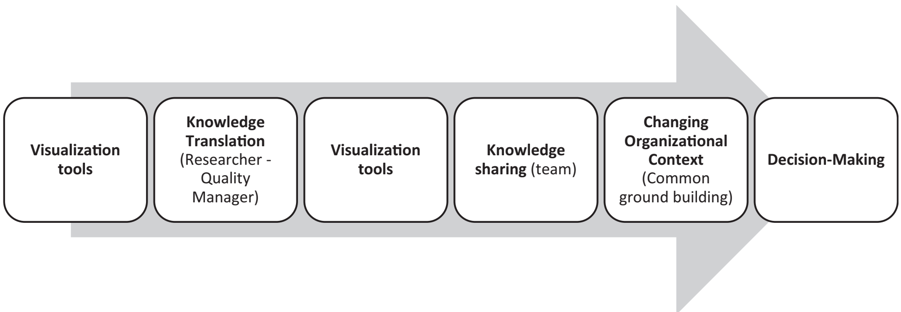

Figure 7.
The dynamic process of knowledge visualization

The "non-visible" dimension of each domain can remain so. The "mathematical" knowledge is fundamental to construct the model, but does not need to be shared with the company. FCA engineers have highly specific knowledge of processes and portfolios, but this only partially needed to be shared with the mathematical experts. The main purpose of the knowledge visualization was therefore to create a "boundary object" (Eppler and Burkhard, 2007) between these two separate "worlds": a common point of reference to facilitate conversation around different domains (Nicolini *et al.*, 2011; Spee and Jarzabkowski, 2009). This distance should not be bridged or shortened but simply respected. The process of knowledge visualization can therefore be interpreted as the "bridge," a tool that facilitates the communication (conversation) between the two worlds, which use different languages and need "common ground" to interact and understand each other. Building this bridge is only one part of the dynamic process that leads to decision-making. The visualization tools (e.g. Figures 1–3, 5, and 6) shown to FCA staff helped to enable interrelated dynamics (Figure 7).

The first dynamic is inherent in the process of translation: *bridge building* (Step 2, Figure 8). In a context where the players are researchers and managers, this bridge could be sustained by translation mechanisms. Simeone *et al.* (2018) stated that, given the different objectives and languages in academic and industrial contexts, translation mechanisms between these two groups of stakeholders are needed to establish a common platform of communication. Visualization tools fostered knowledge translation among researchers and

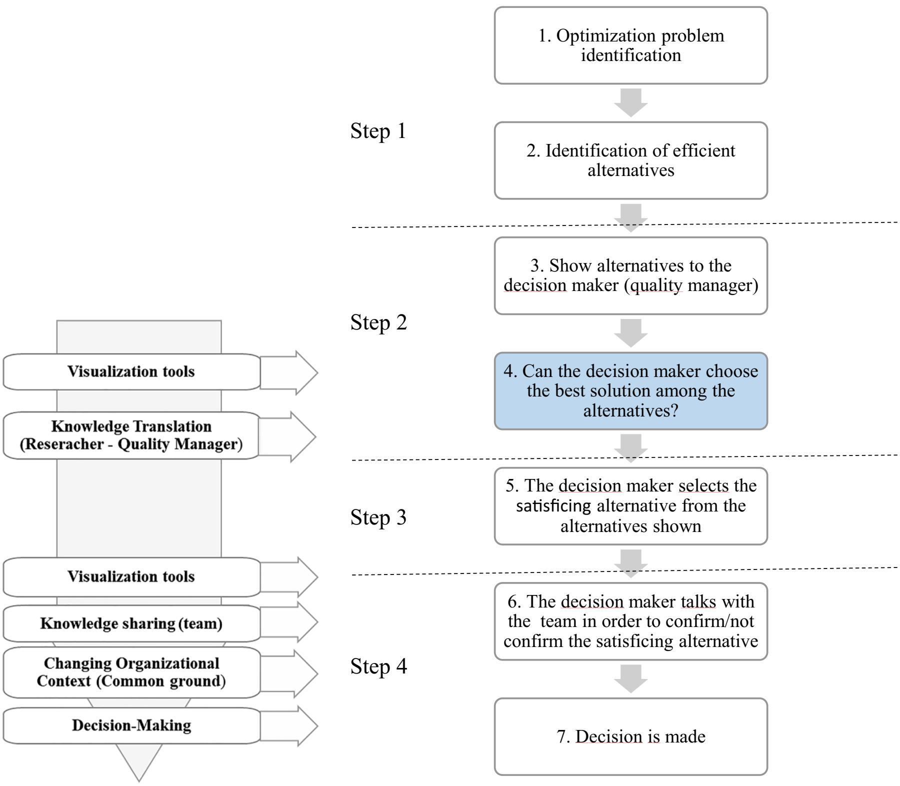

Figure 8.
The location of the knowledge visualization process within the multiobjective optimization steps

the quality manager, creating the conditions for a dialogue between these two worlds (Canonico *et al.*, 2020). These tools also enhanced managerial judgment by translating raw data and information into accessible forms to extract knowledge and selecting the "good" alternatives (step 5, Figure 1). What came before and after was fundamental to reading the diagram, but the diagram itself (Figures 2 and 3) was the key. The images of the critical points of the processes engaged those from heterogeneous backgrounds and enabled inputs from different actors, allowing a fruitful interaction. The quality manager stated:

> The histograms help to intuitively and quickly compare the alternatives available to me and to quickly choose the best alternative to address the critical points of the processes in the plant by severity. [. . .] In making a choice, it was very useful to visually understand the composition of the portfolios as I could understand the exact point of the process in which we could intervene.

The second dynamic concerns the process of knowledge sharing, which occurred when the visualization tools were used to share knowledge with other FCA engineers (quality team) and the plant manager (step 4, Figure 8) (Eppler and Pfister, 2014). These tools helped to define the alternatives clearly, classifying and then prioritizing them. The team highlighted that the visualization tools were useful for assimilating new practices into the company. They found the histograms particularly useful. Visualization tools and knowledge translation embedded in both the researcher–quality manager relationship and collective reflection about the final choice were the keys to fostering knowledge sharing among the members of the team (academics and practitioners).

Templates and *ad hoc* drawings of complex mathematical formulas helped to direct teamwork (Gavrilova *et al.*, 2017b), transfer and share insights and enable quality team members to apply these insights. They acted as facilitators, activating awareness and reactions in group dynamics and supporting the social processes of sharing knowledge with others to make a decision about the upgrade of the lean production process.

The third dynamic, clearly overlapping with the second, relates to the organizational context. A common language breaks down barriers and promotes sharing and participation. It is how the commitment of the top manager (the plant manager) who has decided to participate in the decision-making process acquires a concrete meaning in a collective dimension. The people in the group understood the model and immediately sensed the main benefits. Knowledge sharing among the group clearly spelled out their contribution towards a common endeavor. The activation of knowledge translation, the construction of "common ground," and the sharing of knowledge in a group dimension all supported decision-making and the implementation of a model that can effectively determine the advantages for the quality of the production process, diminishing the number of errors and/or keeping them under control. The quality manager noted:

> The constructed mathematical approach helped us to better understand the problem we want to tackle and the constraints related to the problem considered. [. . .] The synthesis of the alternatives represented with the related visualization tool helped me to create a dynamic process of knowledge sharing with the team members. [. . .] This made it easier to share and involve the quality team in the moment of the final choice.

Knowledge visualization, therefore, goes far beyond the visualization tools themselves (Eppler and Burkhard, 2007). It can be interpreted as the interactional process where different players translate their know-how, share a framework and develop common ground to support decision-making. Our study shows that knowledge visualization is a long and complex process closely related to knowledge translation, knowledge sharing and decision-making. It cannot be considered as a single moment when visualization tools are used. It may, therefore, be better to refer to the concept of *visualizing knowledge*, highlighting the dynamic and process view of our approach.

7. Conclusions

Our study shows how knowledge visualization and the associated tools work to enable knowledge translation and knowledge sharing, supporting decision-making. Our empirical findings showed why and how knowledge visualization could be used to foster knowledge translation and sharing among individuals and from individuals to groups. Knowledge visualization is understood as both a collective and interactional process and a systematic approach where different players translate their expertise, share a framework and develop common ground to support decision-making (Schiuma *et al.*, 2012).

The process of translating and sharing knowledge is particularly challenging in the automotive industry because of the pressure towards process and product innovation. Carmakers' efforts to develop innovation outside conventional firm and supply chain boundaries have driven them to network with a variety of actors, such as academic researchers (Canonico *et al.*, 2018, 2020). We investigated the adoption of a multiobjective optimization mathematical approach in an LPD setting in the automotive sector, clarifying how knowledge visualization could be useful to analyze and select alternatives in a lean production process.

The case study originated within an innovative Ph.D. project, involving a research group of a Ph.D. student, two professors from the University of Sannio, two professors from foreign universities and the quality team at the FCA plant in Pratola Serra.

From a theoretical perspective, our paper has expanded the understanding of knowledge visualization as a system of practices that support the development of a multiobjective decision-making method in interorganizational collaboration in two respects. First, it contributes to the theory of knowledge visualization as a dynamic and longitudinal process. It provides some theoretical and empirical arguments coherent with recent ideas put forward by Eppler (2013). It also provides useful insights by reflecting on how the use of knowledge visualization tools can facilitate knowledge sharing and build up decisions and solutions. Finally, our paper explores how the adoption of knowledge visualization tools may help to support effective knowledge translation.

From an empirical point of view, our results may be useful to other firms in the automotive industry and for academics wishing to develop applied research on portfolio optimization. We showed that if the degree of specialization is high and the problems are complex, it is much more efficient and effective to use knowledge visualization tools to establish common understanding in an interorganizational and interdisciplinary domain. We believe that the adoption of knowledge visualization in portfolio optimization problems could be a promising area in LPD settings, allowing practitioners to manage complexity and stimulate participation, facilitating communication within the group, and improving decision-making processes.

This study had some limitations, which must be taken into account when evaluating its results. First, it used a qualitative approach, so its results may not be widely generalizable. However, this approach was consistent with the study objectives and the nature of the research question. It allowed us to draw insights that may be important in advancing theory. Second, the case study was set in a specific context that conditions our concluding remarks.

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Appendix

Critical Points of the Processes (CPP)	Name of process
CPP 1	DISTRIBUTION SHAFT
CPP 2	CAST IRON BASE
CPP 3	CRANKSHAFT
CPP 4	BASE ALL
CPP 5	JTD CYLINDER HEAD
CPP 6	SHORT BLOCK
CPP 7	TC ASSEMBLY
CPP 8	LONG BLOCK
CPP 9	PICKING
CPP 10	VQM

Table A1.
The process labels

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