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FROM ELICITATION TO STRUCTURING OF ADDITIVE MANUFACTURING KNOWLEDGE

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Abstract

Manufacturing, whether subtractive and additive, requires complex operations and process rules are not so easy to structure or define. Although efficient CAD/CAM software have been developed to support the design and manufacturing tasks, knowledge management systems are still fighting to formalize those manufacturing practices, and the way they impact the design of parts and systems. This paper deals with Additive Manufacturing (AM) knowledge which is still in construction in industries. It aims at proposing approach and method for AM knowledge structuration. A case study about the influence of supports onto the quality of EBM (Electron Beam Melting) metallic parts enables us to confirm the benefits of a collective elicitation. Two elements contribute to its success: the use of an influence matrix and an argumentative situation between experts. Furthermore, four categories of AM knowledge are identified (definitions, examples, influences, and rules broken down in Action Rules and State Rules). They proved to be useful for identifying and structuring AM knowledge in our case study.

Keywords: Additive Manufacturing, Knowledge management, Case study, Design for Additive Manufacturing (DfAM)

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1 INTRODUCTION

Additive Manufacturing (AM) is changing the engineering design and manufacturing practices since a couple of decades. This technology enables indeed to build parts with complex shapes and geometrical features by adding where it is required successive layers of material, whether in liquid, solid, or powder form. Beyond this opportunity, AM technologies also come with their own limitations, and taking the best of it rely on the skills and knowledge of a few number of people. AM experts use various strategies to design or manufacture parts properly but their knowledge is not well formalized and would need organization. There is here an opportunity to capture and formalize their knowledge, and to propose methods to structure information about this activity.

This paper deals thus with the elicitation and the structuration of AM process knowledge. It is part of our ongoing research work aiming at integrating AM knowledge transferable to a Knowledge Management System (KMS) in an industrial environment. Our global objective is to capture knowledge related to AM practice, to analyse it and to structure it, so it can be useful to CAD/CAM AM users. To reach this objective, various experts of the AM process (i.e. part design, manufacturing, finishing, machining and quality control) have to be involved in the knowledge elicitation process. Indeed, according to Wilson (2002) knowledge resides in people's mind, whether explicit or implicit; this remains a challenge to formalize, manage or transfer to other CAD/CAM users. As knowledge intermediary, we assist these people called "knowledge producers" by Markus (2001) in the elicitation and externalization of their knowledge. In a previous work, the testing of some individual elicitation techniques raised contractions between the experts and a poor confidence in the results. This led us to propose a collective elicitation approach in order to get more shared explicit knowledge.

So, the objective of this paper is twofold: firstly to test the relevance of a collective elicitation approach; secondly to capture knowledge content related to the practice of AM experts.
The remainder of the paper is structured as follows: section II states a brief literature review related to knowledge elicitation and knowledge classification, leading to refining the initial research questions. These questions are then tackled through the case study of a collective elicitation session described in section III. Results that highlight some interesting AM process rules and influences are presented in section IV. As a conclusion, the usefulness of the collective elicitation session is discussed and some future works are presented.

2 LITERATURE REVIEW

2.1 Knowledge elicitation and knowledge classification

Knowledge Management (KM) is very often associated with Information System and Knowledge Management System, but also with methodologies to manage experts' knowledge. As far as manufacturing knowledge management is concerned, many systems have been developed. These tools are more knowledge bases, mainly used for storing information about machining routines and tools. Grundstein (2009) proposes a method in five steps (locate, actualize, enhance, preserve and manage) which focuses on "crucial knowledge". According to him this knowledge is crucial as it has an impact on the objectives and the durability of the firm. Applied to an AM context, crucial AM knowledge would be our primary interest. We define AM knowledge as crucial as soon as it has an impact onto the global AM process in terms of cost, part quality and global processing time. AM process we look at starts from the design phase (part geometry optimization) up to the quality control of the final part.
According to Grundstein, knowledge elicitation is used in the first step "locate" of the knowledge cycle. Elicitation is "the process of collecting from a human source of knowledge, information that is thought to be relevant to that knowledge" (Cooke 1994). Elicitation is a means to express the knowledge of experts. It is a necessary step for formalizing knowledge before structuring and sharing with other actors.

Milton (2007) proposes many individual elicitation techniques of knowledge ranging from basic/explicit to deep/tacit knowledge, as well as from conceptual to procedural. As mentioned before, we tested three of them for capturing AM expert knowledge (Grandvallet et al. 2017). Differences and contradictions appeared between experts statements, leading to a lack of confidence or trust with regard to this elicited knowledge. In a product design context, Stenzel and Pourroy (2008) proposed an influence matrix linking design parameters to technical requirements in order to clarify their disagreements. This collective approach experiencing actors' contradictions got indeed constructive feedback was also tested by Baouch (2016). Such a collaborative approach based on an influence matrix seems to be relevant for defining our collective elicitation session.

In terms of classification of knowledge, various authors have tried to characterize knowledge differently. For instance Lundvall (2004) classifies technical knowledge as know what, know why, know how, and know who. Other authors make the distinction between procedural and declarative knowledge. Declarative knowledge could be expressed for example by "I know that…". Procedural knowledge instead would refer to "I know how". In this paper we will focus on a categorization leaning on procedural and declarative knowledge. Our objective is indeed to find manufacturing rules. Rules are commonly defined as prescriptions or conventions to be followed, specific to thought or action, relating to science, technology or action. Thus defined, rules can contain procedural (action) and declarative (thought) knowledge.
The model of Ammar et al. (2005) tries to identify knowledge objects that can support the construction and sharing of designer's knowledge in the context of finite element analysis (See Figure 1).

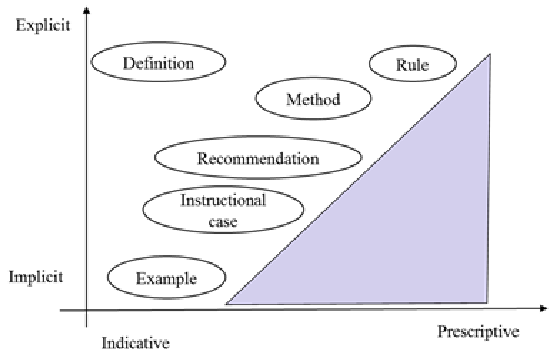

Figure 1. Positioning of knowledge objects, translated from Ammar et al.

This model characterizes knowledge objects according to two axis: indicative and prescriptive, as well as implicit vs explicit. Six types of knowledge objects are identified: example, definition, recommendation, method, and rule. What we retain from this graph are the two axis and two of the objects: rules and examples. Example describes implicitly knowledge implementation and is positioned as indicative because it is only an illustration of the knowledge usage. A rule includes explicitly knowledge and is prescriptive because its status is to be applied in a determined context. Another interesting element is that experts manipulate objects named definition that they characterize as explicit.

2.2 Research challenge and approach

Considering the previous State of the Art and hypothesis we will try to elicit crucial knowledge, whether procedural or declarative, from a collective elicitation. This will enable us to identify knowledge objects to which a degree of confidence will be associated, for qualifying explicit and implicit knowledge.
From the previous literature review, the research questions are refined as:

- Does a collective elicitation based on discussing an AM influence matrix enable Knowledge Engineers to capture AM knowledge?
- Are Rules, Examples and Influence relevant categories for identifying and structuring this AM knowledge?

The global research methodology is based on the dialogical model from Avenier (2009). Practioners (the AM experts) are involved in the research process through the collective elicitation process and by legitimizing the results. These latter are formalised by the researchers. This methodology proved to be relevant in the engineering design context (Prudhomme et al. 2010).
The paper is based on a case study approach in the AM domain. The study consists in a three-step process: Elicit (AM knowledge through a collective elicitation session), Analyze (experts interactions to locate AM knowledge), Structure (the resulting AM knowledge). The first two steps are presented in

the next section whereas the structuration is part of the results section and further discussed in our methodology.

3 CASE STUDY

3.1 The activity of support creation

The scope of our analysis is the design and creation of support structures for metallic parts built with EBM (Electron Beam Melting) technology. An example of supports is provided in Figure 2.

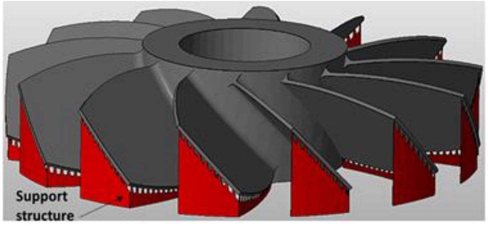

Figure 2. Turbine and its supports built with EBM technology

This activity is in fact critical because it is closely interlinked with the characteristics of the parts as well as the manufacturing parameters. Supports are indeed used for thermal and/or mechanical reasons (Vayre 2014). Hence, they influence the final quality of parts. According to the orientation angle of the part in the chamber of the EBM machine they are sometimes required to stabilize the manufacturing process and to support overhanging surfaces. It is then important to capture rules that can optimize the choice of supports associated to the part in the build.

3.2 Presentation of the elicitation techniques about supports

As explained we intend to formalize knowledge for creating support structures for EBM metallic parts. In our first experimentation (Grandvallet et al. 2017), the results of the three individual elicitation techniques tested with AM experts led us to the identification of many parameters related to supports and influencing the part.
On the one hand we characterized the part performance criteria by the quality, the process duration, and the associated costs. On the other hand, support parameters were classified into three main families: position, density, and shape. A matrix was developed crossing these two dimensions, in order to have experts assess the degree of influence of the parameters onto the product criteria. (See Figure 3).

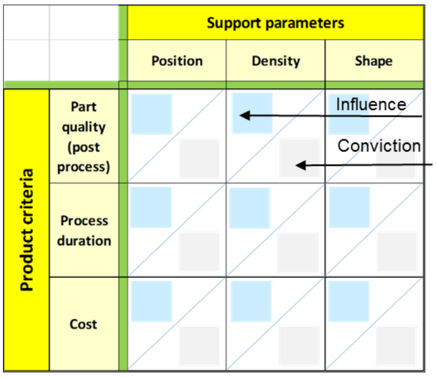

Figure 3: The influence Matrix

To populate each cell of the matrix, we opted for four levels of influence, basically described by three main levels (from none, to weak, and strong) and one possible score entitled “I don’t know” (see Table 1).

Table 1. Influence Levels

Influence level	Correspondance	Definition
0	No influence	The support parameter does not have any influence onto the quality surface of the part
+	Weak	The support parameter has a weak influence onto the quality surface of the part
++	Strong	The support parameter has a strong influence onto the quality surface of the part
?	Don't know	The expert knowledge is not sufficient to explain the support influence

In addition, taking for granted that knowledge has been for ages closely related to belief, the actors were proposed to qualify the confidence they attach to the level of influence they quote. This was done by requesting from them to choose between five degrees of conviction (see Table 2).

Table 2. Conviction Levels

Conviction level	Illustration	Definition	Example
1	I have an intuition but no explanation	Personal feeling, with no proof or precise element.	•*I think that...* •*I would say that ...*
2	I can have a possible explanation but no example	Strong intuition that an event occurs.	•*It may be that...*
3	I could cite a limited number of cases to explain it	Some elements may guide the reply but partially	•*I found 1 or 2 similar examples in the literature* •*I've already encountered the case*
4	I managed to explain it thanks to several converging experiences	Several elements, experiences ou proofs confirm the reply.	•*Each time I was able to witness this*
5	I can demonstrate it	No doubt about this knowledge	•*I've got no doubt about it* •*I can prove it with a rule*

From the first experimentation, parameters and criteria were broken down into sub-parameters and sub-criteria. Tooltips were added to furnish definition of the sub-parameters. Next step was to have it tested individually by six experts, by asking these ones to indicate the influence level of the support structures as well as their conviction level. The aim of this exercise was then to capture experts' knowledge about support influences onto the part.

For this paper we focus on the influence of support placement onto the quality of a part surface. Support placement, or positioning, is one sub-parameter influencing the "position" parameter. Surface quality is one sub-criterion of the part quality criterion, others being: geometrical deformation, dimensional quality, physico-chemical quality, mechanical behavior. (See Figure 4). Once experts filled in their matrices, we analyzed the results and created a synthesis table so that the aggregated scores could be easily compared between each other. In this way we expected to build the beginning of a cartography related to support knowledge.

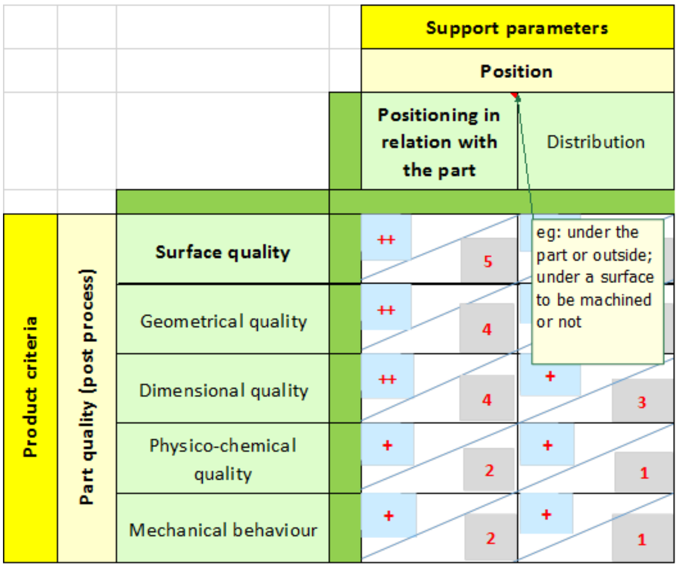

Figure 4. Example of a populated influence matrix (excerpt)

This merge revealed several distinct trends:

- One trend with homogeneous influence levels associated with a heterogeneous conviction level
- One trend with strong influence levels and strong conviction levels (which could quickly lead to a possible agreement between experts)
- and one trend with heterogeneous influence levels and a divergence of confidence levels (interesting for debate)

Figure 5 gathers the results of a specific matrix cell which falls into the first above-mentioned trend: converging influence levels confirming that the placement influence onto the surface quality exists (whether weak or strong); and different levels of confidence associated, one person (E5) with a high conviction level.

		Support placement					
	Experts	*E1*	*E2*	*E3*	*E4*	*E5*	*E6*
Surface quality	Influence	+	+	++	++	++	+
	Conviction	2	2	3	4	5	1

Figure 5. Synthesis of the Influence Matrix of support placement onto part quality surface

Obviously experts did not have exactly the same opinion and knowledge level about support placement influence. This cell was one of the cells discussed during the collective elicitation in the format presented in Figure 5, so as to create an argumentative situation where experts could confront their point of view about EBM supports.

3.3 Approach for collective elicitation

This experimentation was built around two major leverages: the discussions and argumentation of experts about an influence issue, as well as the relevance of an influence matrix synthesis used as intermediary objet. The aim was to set up conditions facilitating both argumentation and knowledge emergence.

Experts gathered in a collaborative experimentation room equipped with video cameras and microphones. They discussed and argued about the content of specific cells of influence matrix synthesis that was projected onto a screen. We moderated the debate as knowledge elicitators. We made afterwards a written transcript of the complete discourse in order to analyze it. Section IV will show below that this collective elicitation is relevant as it allows eliciting knowledge that can be categorized. Besides, we manage to highlight an approach for analyzing the discourse transcribed after the elicitation exercise.

3.4 Approach for discourse analysis

We were three Knowledge Engineers outside the panel of AM experts to read the textual transcription and dissect it. The exploitation of the qualitative data was organized as follows:
A first reading allowed to get a feeling of the text transcribed, and to understand the main idea and the key moments of the debate. According to the conviction level of each expert, the discussion was indeed made of assertions, opinions based on beliefs, agreements, disagreements, and arguments associated. Following this first reading, we could, as Knowledge Engineers, share our understanding of the main concepts discussed about supports for AM process and know the basis about these supports.
A second reading helped us to identify key syntaxes in the text. A simplification was done with least personal interpretation by eliminating words polluting it (such as hesitations and needless repetitions) and by locating the most significant sentences. The aim was to check if we were able to locate at least examples and rules as suggested in our hypothesis, as well as possible influences. According to their meaning, some sentences were then highlighted in colors, proven that we were able to use this grid for making an analysis.
A test of this grid was undertaken next to validate it while locating these categories.
As a result the presentation of the information categories is given in the next section. But we keep in mind that our understanding and categorization we made need to be validated by the AM experts.

4 RESULTS

4.1 Knowledge categorization

The three main categories of knowledge identified were relevant for analyzing the transcribed tracks of this collective elicitation session about the influence of support positioning onto the part quality surface. They concerned:

- **Influences** of some support parameters onto the part or the manufacturing process itself
- **Examples** of real life part building cases or situations in relation with the topics, references to some specific tests
- **Rules** about where and how to place or position supports onto the part

But for being exhaustive in the analysis, another category had to be added: **Definitions** of technical terms related to support structures. It is not really a new category in itself since we discussed about it during our literature review, but it proved its relevance in the analysis of this transcript.
Definitions are closely related to the concept of cognitive synchronization (Darses et al. 2000). They contribute to the building of shared understanding between people. They were provided by the actors at the beginning of the session or even during the discourse when doubts arose. Agreeing on common understandings on terms as for instance “positioning”, or “surface quality” was a departure point for exchange on the discussed topic. **Definitions** are of a different nature from the other categories as they were used to enrich them, but this category was necessary to analyze the transcribed speech. Table 3 draws a list of the **Definitions** proposed by the experts during the collective elicitation session.
Influences emerged during the debate in the form of “this depends on…” or “this impacts…”. Identifying some influences from this transcript is of course not very surprising since they are at the heart of the influence matrix, used as a starting point for the discussion. Table 4 lists the different **Influences** caught from the analysis of the transcript.
Examples were given each time an expert felt the necessity to reinforce his argument or explain his results by resuming the conditions or the context. Table 5 sums up the three **Examples** used by the expert during the session as well as arguments that we detected behind them.
Lastly, during their argumentation, experts expressed Rules and the conditions of their application. Some of them were specifically given in terms of “if [or when]…then…”. Others were either uncomplete, perhaps because of the lack of deepness of the actors’ knowledge, or not so obvious to capture and required interpretation from us. For instance the statement “in case of a support touches a surface, when you remove it, you will leave marks onto the surface” is transformed by us into “if support on surface, then removal. And if removal then surface marks”. This writing format leads to a more formal language.
A deeper analysis was then done subsequently to better characterize these rules. This was done by first grouping them according to the topics treated. We managed thus to highlight two distinct rule categories: **Action rules** and **State rules**. They relate to procedural and declarative knowledge. Whereas **Action rules** imply to act and to reply to questions such as “How do I do to place my support?”, **State rules**

can be considered as facts or principles that describe statements and explain the world as it is. An example of a **State rule** is: support removal implies the damage of the part surface quality. Table 6 classifies and restructures both rule categories and encodes them in a language close to an information system one. A designation of a rule is determined by the second part of the syntax: "if [statement] then [statement]" is obviously a statement rule. However "if [action] then [statement]" is a statement rule, whereas "if [statement] then [action]" is an action rule.

4.2 Contents of categories

The tables below provide examples of the four categories resulting from our analysis. They have yet to be legitimated afterwards by the AM experts who participated in the elicitation session. However, some statements have not been included into the tables as they were not clear enough. For example, an expert mentioned the shape of supports as follows: "if we do parallels or squares…". This would require more explanation from his side, which could have been done after the session.
The **Definition** table (Table 3) was rather easy to construct based on the discussions. They remain temporary definitions since they were used to argue about an influence or a rule description.

Table 3. Definitions proposed by the experts

Term	Definition
Support positioning	Can be under the part, outside the part, under a surface that needs to be machined or not. Can be something coming from the sides of the part.
Surface quality	Means here rugosity. Form defect is not associated with surface quality in this context because it is a geometrical defect and not a surface quality.
Support	A support is something that does not remain on the final part.
Support distribution	Support distribution can be either only under the part contours or uniformly distributed over the surface.

The **Influence** table (Table 4) points out the main influence of one element on another. This helped us to highlight the main elements and their relation in the activity of support placement.

Table 4. Influence description

Influence description	Of what	On what
"If we scratch beforehands with a file or a Dremel some material is then removed, and the marks done by Dremel disappear when sand peening."	Finishing	Surface quality
"This also depends on the way the support is removed."	Support removal	Surface quality
"There is an influence on the surface we get post AM. And this potentially influences the process onwards till the finished part which will requires potentially a machining process or a Dremel finishing. I'm sure this damages the surface quality at the end of EBM process. And then, according to the scheme, i.e. the manufacturing process followed by the part, this will have or will not have an influence onto the final part."	Surface quality at the output of AM building	Post processing machining
"As soon as you place supports onto a surface you know you get damages in terms of surface quality."	Support placement	Surface quality
"The positioning of support will directly impact the surface quality of the area where it is positionned."	Support positioning	Surface quality

Examples were proposed by the experts to argue the influence level they assigned to the support placement.

An analysis of these examples enabled us to capture the key ideas expressed by the actors and to understand the usage of these examples. This confirms that examples are used to illustrate influences or rules and to crystalize the knowledge although they do not make it emerge. (See Table 5).

Table 5. Examples details

Example	Main topic	Usage
"We noticed with some students that if you put supports outside the part that are enough massive and absorb heat, this is the most flat surface you've ever seen. They [the students] built rather parts than supports."	Support typology	Used as a pro argument to claim that supports do not always need to be placed under the part.
"Recently we made a part for tensile testings and we observed what happened. Actually we made a mistake and built it 2mm from the startplate, it was rather masive, with 8 or 10mm thickness and 120 length. [...]Yes it was started on the powder and the built went very well without any problem […] and if we look at it...on the powder, with no support, and if we look at the surface behind.. the surface roughness is correct."	Building process	Used as a pro argument to explain that a part built on powder with no support is an alternative for a good surface quality, if it is close to the startplate (2mm).
"I remember the part we built for X. Removing the supports left many little pins evreywhere and this was not aesthetic. But you may not care about that, depending on what you do with the part, if it is inside of the motor".	Part surface quality	Used to support the idea that removing the small pins is not mandatory if this surface is not visible once integrated in the final mechanism.

Regarding rules, the discussion between experts revealed that AM rules concerned not only support positioning but also actions outside the process, for example post processing rules. (see Table 6).

Table 6. Action rules and State rules

Action rules
If support on a surface then removal
If support then machining
If marks then shot peening or Dremel abrasion
If support then Dremel abrasion
If support then finishing of supported surfaces
If surface not nice and if customer requirements then shot peening
State rules
If removal then marks on the surface
If support then damage of the surface
If machining of supported surfaces then no influence onto the surface quality
If machining on the final surface then no support influence
If Dremel abrasion then no support influence
If support removal and no Dremel abrasion then pins

5 CONCLUSION

This research work in three steps - elicitation, analysis, structuration of AM knowledge - lays the foundations for a methodology and knowledge management system. As Knowledge Engineers we focused our study on the influence of support structures onto EBM parts. We chose to implement our method in a case study specifically linked to the influence of the support positioning onto the surface quality of an EBM part.

Individual elicitation answers of the experts were synthesized into one table, which became an intermediary support for a collective elicitation session. During this session we managed the six experts to make them exchange their knowledge and conviction levels about the support influence onto the part surface quality. After the textual transcription of the verbal interactions, we developed a grid that allowed us to make the discourse analysis. The results confirmed that knowledge elicited during the discussion was related to several categories of knowledge: **Definitions**, **Influences**, **Examples**, **State rules** and **Action rules**. This knowledge can therefore be considered as AM crucial knowledge since this part of the impact of support parameters onto the AM process in terms of part quality. However the level of conviction scored by the experts in the influence matrix shows that knowledge is still in construction. Next steps of this work will be: legitimation of the results by the experts; news collective elicitation sessions related to the other cells of the influence matrix; integration of the results into an ontology for a KMS. Since the full process of collective elicitation as it is proposed here could be time consuming, which is an important limitation of the approach, some further work will also be carried out in order to reduce this time. This can be done by providing guidelines for reducing the influence matrix, and for identifying the most relevant cells to explore within this matrix. Another way forward could be a semi-automated identification of the rules from the debate corpus.

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