Development of Spare-Parts Process Chain in Oil & Gas Industry Using Industry 4.0 Concepts

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***Abstract*—Through the expansion of Industry 4.0, the Oil & Gas industry in the world is undergoing a major transformation, so that the formalization of a process chain for the manufacture of spare-parts becomes increasingly necessary. This work aims to create work patterns using the concepts of industry 4.0 applied to the Oil & Gas industry, through the study of several work- pieces of this area. All spare-parts were used to create a chain of manufacturing processes. From there, they were recreated through different digital or hybrid manufacturing techniques. Several points such as geometry, type of acquisition of geometry, types of raw materials, types of manufacturing technology and machinery were addressed. Mechanical tests were carried out at different stages of the process. The results obtained formed a basis for strategies aiming solving problems of the studied spare-parts, using hybrid and additive manufacturing techniques, combined with the concepts of Industry 4.0. The created protocol was a descriptive and detailed standardization of the production chain process. The evaluation of the processes, justifications and solutions was applicable for each demand, generating a virtual catalog of spare-parts and that fed a cyclical model of experiences that continually update the database itself.**

***Index Terms*—Additive manufacturing, digital manufacturing, hybrid manufacturing, industry 4.0, process chain, oil & gas industry.**

I. Introduction

Additive Manufacturing (AM) technologies have been developed since the 1980s [1], it is a method of building three- dimensional models made using specific equipment whichbuild parts by deposition of raw materials layer by layer, which differs from conventional methods (CM) of manufacturing carried out from the removal of the material, referred to as method or Subtractive Manufacturing (SM), and also by the use of injection molds. Advances in Additive Manufacturing technologies have mostly demonstrated a reduction in raw material expenditure, making the manufacturing process more economically viable and sustainable than Conventional Manufacturing [2].

The use of Additive Manufacturing technologies allows the development of complex geometry parts, and with a wide range of variables to build models with filling, material variation, technology type variation, employing a substantial nuance of options to analyze the best suitability for building a 3D model [3].

In the context of additive manufacturing, several process chains were proposed, as presented in [4], in which the authors present a two-dimensional proposal of a production chain using an evaluation of the internal construction of the parts. The authors also compare it with the common linear structure of a production chain, demonstrating that a two-dimensional approach is more effective.

In the third chapter of Book *'Additive Manufacturing Technologies'* [5], the authors attempt to describe a generalized process chain for the use of additive manufacturing. In this chapter and throughout the book, eight steps are describedfor building this generalized process chain in order to build a generic production line using Additive Manufacturing. The eight steps described are:

- Conceptualization and CAD;
- Conversion to STL;
- Transfer to Additive Manufacturing machine and STL filemanipulation;
- Machine setup;
- Build;
- Removal and clean up;
- Post-process;
- Application.

This defined process chain generalizes and improves the proposal in [6], which is focused on DMLS (Direct Metal Laser Sintering) technology. According to website *'spatial.com'* [7], the eight steps are grouped into four so that the process chain is divided into:

- CAD model building;
- Pre-processing;
- Printing;
- Post-processing.

However, with the inclusion of industry 4.0 concepts, the entire production chain underwent changes as a whole. These changes are interestingly presented in [2], which compares subtractive manufacturing with digital or hybrid manufacturing and its impact on the automobile industry in general. Further- more, they are also presented in the article *'Hybrid process chain from die casting and additive manufacturing'* [8], which points out a chain of processes for die casting and additive manufacturing.

The Oil & Gas industry has characteristics completely different from common industries. This happens because the effective product of this industry is not manufactured, but extracted from a raw material, as shown in [9], which mentions that: *'The oil and gas industry is involved in a global supply- chain that includes domestic and international transportation, ordering and inventory visibility and control, materials handling, import/export facilitation and information technology'*. Proving to be a world-wide supply industry.

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Thus, the general process chain in this sector cannot be impacted by preventive or emergency maintenance problems in prospecting equipment, as they are often found in remote areas or areas with difficult access. Furthermore, this interruption cannot interrupt the process, as this is an increasingly competitive industry [10], [11]. However, equipment maintenance operations are common, which can occur at any stage of the production chain.

Hence, the extraction process can be interrupted many timesdue to the failure of parts of a specific machinery. In this way, the maintenance teams request replacement of parts, demanding certain replacement items of machinery that are difficult to supply quickly, which often present high creation cost when generated by Conventional Manufacturing. In some cases, the replacement of parts using the Conventional Manufacturing method may not even be possible because they are no longer in the production line. The lack of these items invariably causes delays in preventive and corrective equipment maintenance. Some strategies to avoid this spare-parts problem can be seen in [12].

The Industry 4.0 concepts can be used to improve setup time and decrease production downtime. This is because with Industry 4.0, the virtualization of spare-parts allows to have a virtual stock of parts, which can be printed directly from the platform or workstations. In addition, other aspects such as *'Industrial Internet of Things'* (IIoT) are essential for an increasingly dynamic work of communication between all layers of the production line, as described in [13].

Furthermore, as presented in some articles, the transformation generated by the insertion of Industry 4.0 in the oil industry reaches aspects of productivity [14], storage control and data management [15] and business plans [16].

The present study will use the concepts of industry 4.0 focused on the spare-parts manufacturing process. The study consisted of several spare-parts of different types and purposes. The entire process was carried out during 24 months, in whichdata from technical-scientific investigations regarding the execution of spare-parts by different types of manufacturingprocess were used.

The project was carried out in partnership with an Oil and Gas company in Brazil. This study aimed to optimize the resources of Digital or Hybrid Manufacturing in order to accelerate the development process and availability of spare-parts, generating a standardization of the production process and virtual cataloging of spare-parts.

II. Preliminary Analysis

As presented in the previous section, an extensive evaluation was carried out during the study, consisting of mechanical tests, evaluation of procedures, evaluation of materials and formalization of the process chain. This section will describe all assessments in order to justify all choices and define the standardization of processes.

The analysis and research on advanced manufacturing methods was carried out, where we sought to strongly explore studies on Additive Manufacturing standardization, in order to promote the best use of this technology with real applicability in the industry [17]-[19]. To create a chain of processes it is necessary to gather information about every possible technique to be used. Thus, it was necessary to create a database containing information on the entire technological structure available and with possible process variables, as well as other important points obtained. In this way, the following information were collected:

- The specifications of Additive Manufacturing technologies and processes (such as SLS/DMLS/FDM/SLA);
- The specifications of Subtractive Manufacturing technologies and processes (such as milling/turning);
- The specifications of all machines available in the lab;
- The specifications and characterization of all materialsused in these machines;
- Mechanical, thermal and electrical resistivity tests to confirm specifications;
- Softwares for simulations, measurements and model generation.

Furthermore, part of the database content includes the analysis of literature studies, such as the evaluation of the mechanical behavior of printed specimens [20]-[23], as well as research on the processes of influence in guiding the material deposition process by Additive Manufacturing

Ref. [17]-[24]. The creation of the database also aimed to concentrate the information obtained in the experience of executing spare parts by Digital Manufacturing, within a project carried out for the Oil and Gas industry, having created parts of different models, objectives, materials and technologies, being a very diversified material, with ample information.

For all study items, a list of individual technical sheetswas prepared, in order to descriptively document the technical advances obtained in the analysis and execution processes of the project study items, creating a history that can be accessed at any time to optimize processes futures.

These sheets contain item specifications, information about the condition of the original part (e.g. type of damage, superficial finishing), technical drawings, raw materials, suggestions for the use of new materials (when relevant), model modifications for improvement, developing of new designs, andall the history of spare-part production by Digital or Hybrid manufacturing, relevant tests performed and performance of the replicas in relevant test environment.

A. Laboratory Infrastructure

The infrastructure of the laboratory used for the research has at least one 3D printer of each type, in order to compare which type of process obtains the best result for each type of part. In addition, it has two types of scanner, a machining center, a lathe machine, a robot arm with settings for milling and cuttingStyrofoam, a grinding machine and a wire-erosion machine (Fig. 1). Furthermore, the laboratory has a machine for tensile and compression testing and hardness testing machine.

Fig. 1. Infrastructure of the laboratory.

It is important to note that this infrastructure is smaller than that of a large industry. However, the laboratory equipment was chosen and acquired in order to represent a micro-cell of a Tool and Die Plant which can be simply implemented in an offshore environment.

During the study, the laboratory used three CAD software (*Powershape*®,*Rhinoceros*® and *Solidworks*®), each with a different objective.

B. Materials

The choice of materials to be used varied according to the type of part and the processes used, however, in order to standardize some steps, it was defined that all volumetric prototypes would always use the Fused Deposition Modeling (FDM) technology by be less costly than other technologies. After all the volumetric evaluations were made, tests were always carried out to define a substitute material (when possible). Also for the purpose of standardizing the process, the following materials were limited according to technology:

- FDM Technology - PLA (polylactic acid) or ABS (acrylonitrile-butadiene-styrene);
- SLS Technology - PA2200 (similar to Nylon 12);
- DMLS Technology - PH1 stainless steel (similar to AISI302 alloy);
- Milling and lathe - any material.

It is important to emphasize that these standards have been altered in some cases in which some specific mechanical or electrical characteristic was needed, according to demand. The decision to change was always accompanied by specific tests, defined in the laboratory.

C. Origin and Function of Pieces

All pieces evaluated during the study were from the offshore environment. Difficult replacement parts were chosen (e.g. long manufacturing time, manufacturer no longer exists). Furthermore, parts with little useful life and that needed frequent replacement and parts belonging to equipment that had already gone out of production were chosen.

Some of studied pieces arrived at the laboratory damaged and, in some cases, only the technical drawing or scale photo of the pieces was provided. In these cases, the laboratory team performed the 3D modeling and PLA printing in order to verify the fits and shape of the part to be studied.

All the preliminary analysis was important to define the directions of the process, verify the challenges and demands and prove that the structure defined in the laboratory would be enough to execute any part of the offshore industry. In the next section, all the methodology created will be presented, defining all the procedures performed in the study.

III. Methodology

As described in the previous sections, it was an active study for the production of a digital fabrication protocol. During the period of two years the parts built served to consolidate a database where a series of relevant information was added, referring to specifications, chemical and physical properties and presentation of raw materials.

All data from the digital or hybrid manufacturing technologies used were cataloged, so that it was possible to create an information base for technical and direct evaluation of each demand sent. Based on information from the original parts and the correlation with the database, the possible paths to be followed for each spare-part were traced. In addition, all tests performed on spare-parts and specimens with materials and processes also created a database and knowledge that helped define the complete manufacturing chain.

Thus, the preliminary analysis (case studies) was successful, demonstrating that a chain of common processes can be applied in most cases. This process chain was elaborated and divided into three major steps. They make up three important phases of the production process and will be described throughout this section.

A. Phase I - Digital Archive Generation

The purpose of this phase is to evaluate the original part or original part information to generate the entire virtual representation. This phase is the composition of the first three steps described in [5]. Furthermore, it outlines an important point of the industry 4.0 concept, which is inventory virtualization, as described in [2].

During the process, it was verified that the original parts can come in different forms, so the following forms are listed:

- Complete technical drawings and datasheet;
- Scaled photo of the original part (in X, Y and Z orientations);
- Physical sample (example of part damaged or not);
- Virtual triangular mesh Model (STL).

For each source of demand has its peculiarity. In case the original part is a 2D technical drawing, the team must perform the three-dimensional modeling as specified, been used directly for Digital Modeling.

When the demand is just a physical sample, the team must perform the virtualization of the original part through a 3D scanner or similar techniques, in order to create a virtual modeland all technical drawings for cataloguing.

In case the demand is a scaled photo of the original part, the team must perform the three-dimensional modeling for the execution of drawings and after the construction of a real volumetric model in order to verify the dimensions and shape of the spare-part to be manufactured.

The entire routine and process chain of this phase was defined, cataloged and transformed in the flowchart of the Fig. 2 below:

It is possible to observe that the flowchart presents the process chain described in the first phase, having phase and III as a link, depending on the situation in which the demand was initiated.

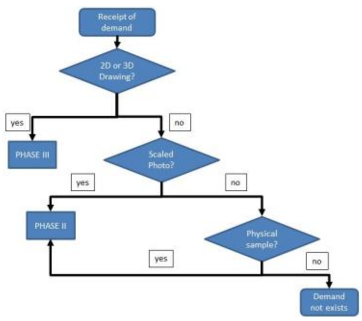

Fig. 2. Flowchart of phase I.

B. Phase II - Analysis of the Demand

In this phase, are used the data obtained by the demand specifications, referring to the parts, with technical information such as the type of materials in which the original part was manufactured, description of the use of the original part, information on the efforts suffered during its use. In addition, information such as the useful life of the original parts and working environment are requested, in order to research possible improvements in the original design in order to increase the useful life of the parts, increasing the time between routine maintenance.

During the process the following evaluations are listed:

- Material evaluation;
- Project evaluation;
- Compatibility evaluation;
- Definition of Manufacturing Technology.

In each process, a detailed evaluation of a constructive com- ponent of the spare-part is carried out. In case of evaluating the material, the data and specifications of the original part are verified regarding the raw material corresponding to the manufacturing process. If the material specification has not been provided, it is necessary to analyze the original piece to determine the material and mechanical properties, find optionsand make any possible changes.

An important observation of this step is that all evaluations go through a validation process through due mechanical tests and through customer approval, in order to ensure that the improvements or replacements performed have a performance in accordance with the need. In case any suggested alteration does not satisfy the specifications, the entire evaluation processis revised, in order to guarantee the success of the action.

The entire routine and process chain of this phase was defined, cataloged and transformed in the flowchart of the Fig. 3 below:

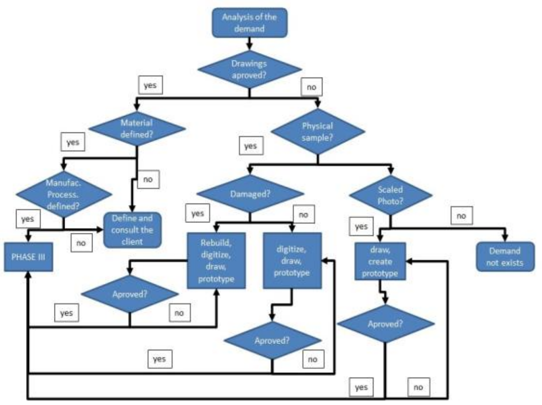

Fig. 3. Flowchart of phase II.

The flowchart above presents different lines of action, as each assessment impacts the others. in addition, if the demand is not approved in phase II, it can go back to phase I, in order to readjust the virtual model to the work process.

C. Phase III - Execution of the Demand

In this last step, every demand must go through some processes for its execution, varying according to the form of receipt of the demand and the type of demand. However, all demands can be allocated in three major steps:

- Dimensional validation;
- Evaluation of the remanufacturing;
- Effective manufacturing of the demand.

The 'dimensional validation' step consists of the trivial reconstruction of the demand in merely representative mate- rial, in order to constructively verify and validate the virtual model. For all forms of construction of dimensional validation, dimensional measurements are checked. The validation process is carried out using a coordinate table, digital pointers, micrometers and other measuring equipment.

The 'evaluation of the remanufacturing' step consists of performing several mechanical tests. These tests can be in the spare-part or in specimens. In the set of studies carried out, the following possible types of mechanical tests and measurements were defined:

- Ultrasound;
- Penetrating liquid;
- Laser interferometer;
- Tensile test;
- Compression test;
- Hardness test;
- Charpy test;
- Flexion test.

In addition, performance tests were performed, with the aim of verifying whether the suggested changes were able to increase the useful life of the parts studied. These performance tests were performed through simulations via software and also with the insertion of the part in the original work environment. The tests verified the overall integrity of the equipment's functioning and items such as leaks, fittings, deformations in work and wear.

Finally, mechanical simulations were made using CAE software, where the finite element method can be used to analyze the part when it is in operation. The results obtained are evaluated to verify the conformity of the part.

The 'Effective manufacturing of the demand' step consists in the building the spare-part for use. At this point, the demand must have been successful in all the previous stages. In this way, the evaluated and approved processes form a construction sequence, which guarantees that any and all similar demands are made identically and with the technology described in the previous items. It is the finalization of the demand itself, which has so far produced a technical sheet with all the history which is stored and cataloged for subsequent requests.

It is important to note that the parts may or may not undergo a surface finishing step, which will vary according to the part and the technology in which it was manufactured. All tests and analyzes serve to ensure reliability in the construction of the part, in order to track possible anomalies, such as, for example, a batch of parts not having the stipulated useful life. After this construction and verification, the demand goes to use.

The entire routine and process chain of this phase was defined, cataloged and transformed in the flowchart of the Fig. 4 below:

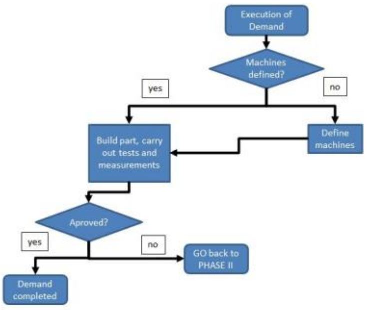

Fig. 4. Flowchart of phase III。

As in the previous phases, depending on the test results, the demand can go back to the second or first phase, in order to guarantee that the demand is met.

D. *Comparison of Techniques*

The protocol elaborated in the previous subsections was validated throughout the study, being improved and adjusted for the production chain of the Oil & Gas Industry, although it can be applied in a generic way, such as the studies mentioned in [5], [7].

Thus, the use on a small scale has been applied for a long time. However, the possibilities offered by this technology, already justified by research carried out over the years, tends to grow for use in medium and large scale. In this way, studies regarding a standardization for the use of additive or hybrid manufacturing has been increasing, precisely in recognition of the next stage of this technology.

Comparing the two studies already mentioned, there is an intersection with the present study, as the chain of digital manufacturing processes has several similarities. However, each type of industry has specific needs, which makes the standardization of the production process extremely urgent.

Therefore, it is important to point out that the use and descriptions of the Protocol proposed in this study, sought to demonstrate specific details of each step, still emphasizing the need for a broad preliminary analysis of a demand, applicability of information from a database and mainly the use of hybrid manufacturing as a strategy for complex processes.

IV. Conclusion and Future Directions

Due to the complexity, difficulty and urgency of replacement parts, in the Oil & Gas Industry, there is a growing demand for the use of innovative technologies and alternative access for their construction. In this study we describe a process chain for manufacturing of spare-parts by digital or hybrid manufacturing, detailing all phases.

The parameters and variables evaluated throughout the study, such as essential data on processes, prototyping machines, raw materials, mechanical tests, analysis of print orientation, were great guides to introduce and guide the production chain of different parts. It is important to emphasize that their use is a great analysis for the effective use of this script, being an essential prerequisite for the entire process.

Another point of the study is the possibility of optimizing the production process of some spare-parts, ensuring an increase in their useful life, which consequently also reduces the demand for preventive maintenance.

Thus, the study presented the following advances, as shown below:

- Standartization of processes;
- Optimization of production;
- Formulation of minimum structure;
- Creation of database of processes;
- Creation of database of materials;
- Creation of database of Virtual models.

Finally, as future directions, there is the implementation of this study in medium and large scale on oil platforms and refineries, in order to shorten the spare-parts replacement time.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Felipe C. Gouvea and Ana Rosa F. A. Martins conducted the research; William S. Barbosa developed all the procedures; Renan F. F. Wanderley performed all the experiments; William S. Barbosa and Simone L. R. Belmonte wrote the paper; all authors had approved the final version.

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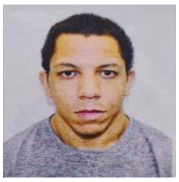

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