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STANDARDIZING THE PROCESS INFORMATION FOR MACHINING OPERATIONS THROUGH SELF-CONTAINED STRUCTURES

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ABSTRACT
A mechanical product is manufactured through multiple processes and procedures. The process information is coded in a part program, and a large amount of unstructured information comes from the shop floor. This results in the loss of logic formulated for the creation of the code. Moreover, it is impossible to track the modifications carried out during these processes. Thus, the unavailability of appropriate and standard knowledge of part processing leads to the situation where the information must be recreated every time a similar part is manufactured, hence, increasing the process planning time. One solution is to divide it into two steps: first, by fetching the information and coding it in a standardized structure; second saving it in a suitable form, facilitating in improving the efficiency and effectiveness of process design for available parts as well as anticipating the new parts. This was done by using the previous information related to the process combined with the one coming from the shop floor. The proposed work concerns capturing the unstructured information from the existing part programs and regaining it using process simulation (VERICUT). Through the extraction of theoretical and graphical geometric data, the interactions between the operations were analyzed. The operational knowledge in this work includes: origin, feed-rate, rotating speed of the tool, rapid movement, cutting tool, material knowledge, and some geometric information of the process. The proposed approach based on simulations and mathematical programming logic is a way to improve flexibility at process and system level by formalizing the available operational knowledge. To illustrate the applicability of the proposed approach, a case study was carried out on a real industrial part program.

Keywords: Process information, Geometric information, removed volume, NC part Programs, knowledge extraction

1. INTRODUCTION
The globalization of the world's economies is a significant challenge to local industry, and it is continuously pushing the manufacturing sector to its advanced transformation integrating innovative technologies in both product and processes. Manufacturing has gone through significant variations throughout the first, second, and third industrial revolutions and is now witnessing the fourth one. Powerful and robust data analytics, Artificial intelligence, expert systems, and learning methods have made knowledge-based decision-making feasible in real-time applications. This proposes new ideas for managing the foremost economic contributors, including small and medium enterprises (SMEs) [1]. The future of these SMEs relies primarily on their capability to respond to the variations in product design and client's expectations while keeping a reasonable economic advantage on the market. To attain this, SMEs are required to thrive consistently to enhance their industrial management processes, i.e., process and production planning, use of different resources, and evaluation of operational performance [2]. Development and evolution in products, processes, materials, and technologies upgrades the manufacturing landscape. In the past decade and a half, mass production has been replaced by low volume production for product variants. The product's design and its manufacturing capabilities are closely related; not only were these new low volume products required to be innovative, but they should be customizable and sustainable [3]. In this instance, A Tolio, et al.[4] proposed a co-evolution model, stating that the process, product and system modifications are interconnected. The concept of co-evolution in product families and assembly systems were presented as a methodology for designing and reconfiguration of manufacturing systems across the product generations [5].

Manufacturing companies have collected a significant quantity of information while designing a product and the processes of manufacturing. This has become an important knowledge resource for the company. The rules of process design are an imperative portion of process design knowledge. This work focuses on the manufacturing processes that are continuously evolving in response to the change in the product and production system. Product design changes can often be predicted; however, sometimes it goes beyond the available design range. This necessitates the accessibility of innovative enablers and adaptable mechanisms to minimize the consequences of these variations in manufacturing [6]. For this reason, industries need to be responsive in order to accommodate the production of parts either new or variants. Moreover, whenever there is a need to re-manufacture, the unavailability of standardized information delays in process planning time and has a terrible impact on the process and system level.

More specifically, this work aims to propose a programmatic approach through which automatic filling of self-contained structures. Kinematic modeling of machines could be possible for improving flexibility of systems and processes, avoiding deviations and uncertainties. In this research work, the intention is to present the formulation of operational knowledge from the subset of part programs. Using the knowledge resources and improved digitalization can be a way to achieve responsive and connected manufacturing. In this way, the co-development of products and processes could adjust to the varying market demand and conditions in factories and enterprises. The remainder of the paper is arranged as follows. A brief overview of the related work and existing approaches are discussed in subsequent section 2. Later, the identified problem is highlighted in section 3, followed by the proposed solution in section 4. The details of the case study part and working of the methodology are illustrated in section 5, and the obtained results are discussed in section 6, and finally in section 7 the presented work is concluded, and future recommendations are suggested.

2. STATE OF THE ART

Industrial globalization in the 1990s created intense competition leading to variations in product design and shorter life cycles. Manufacturing systems need to be intelligent and adaptable to market fluctuations with better flexibility [7]. Various approaches and models have been suggested in the literature regarding the state of art methodologies in manufacturing along with the strategies for forthcoming research and developments. The hypothesis of a modern production paradigm was presented by Colledani, et al. [8], emphasizing the opportunities and challenges for manufacturing industries. Computer-aided process planning (CAPP) systems have tried to answer these market trends, increasing their level of flexibility, and partially filling the existing gap among process planning, production planning, and scheduling [9]. Commercial CAD/CAM systems are considered efficient for part modeling and generation of tool paths. However, they offer a relatively low degree of automation of process planning tasks. Moreover, it is being observed that there is an inadequate link between NC part programming and CAD. In order to bridge this gap, an approach proposed by Miao et al [10] was to use the features in automating few process planning tasks and integrating modules in commercially available CAD/CAM software. Automated process planning involved two major tasks: feature extraction and feature-based process planning. Borgia et al presented the setup for planning problems based on mathematical programming on machining centers STEP-NC compliant data structure [11]. Another research contribution assesses the effects of the process flexibility by accommodating new process planning methods with high scientific and industrial value overcoming the system limitations [6]. This article emphasizes the requirement of increased knowledge about the production resource state at the shop floor level. To solve pallet operation sequencing problem, an automated approach was proposed by S.Pellegrinelli and T.Tolio, in which the complete sequence of production was defined by minimizing the estimated non-production time using a mathematical model [12]. The integration of the process and production planning was carried out at shop floor level and machine all the workpiece on a pallet, improving the productivity and reducing cycle time. A method of extracting thinking process rules for process design been proposed by Jing Tao Zhaou et al [13] to realize the reuse of process knowledge, hence improving the quality and efficiency of process design. This method was composed of two steps: firstly, the instance representation model of process planning reflecting the thinking process of an experienced supervisor has been formulated, and the relevant events been extracted; secondly, the data been pre-processed using manifold learning algorithms and clustering analysis.

An approach highlighting the concept of a network part program for the machining of multiple pallets proposed by Borgia et al [14] conferred an increase in flexibility at the shop floor level. A machining sequence was defined by a machining system supervisor and generated the related parts just before the execution of the pallet. These machining working steps and the G-code instructions were elaborated at the shop floor. However, this approach was only limited to 4-axis machine tools and lacks the automatic recognition of precedence constraints. Interestingly, an approach was proposed to verify the machineability of a pallet configuration given an existing part program. The machining environment was represented in 3D to detect collision between parts and fixtures [15]. In addition to existing work, Tolio proposed a methodology for automatically partitioning a part program into fundamental operations using collision detection [16]. New products with embedded intelligence, design and control allows autonomous planning, operation, and execution.

Summarizing the literature, most of the emerging approaches have flexibility and adaptability towards the changing demands; nevertheless, there is a need to systematize the existing methods to support their machining operations. The proposed research covers the domain of extracting operation knowledge and saving it in an appropriate format to recover the functional and useful information related to processes. This approach fills the gap by standardizing the knowledge at the operational level, starting from separating the knowledge of part program and system. The most technical issue is to regain these parameters associated with the processes. After the first use, it requires configurations and models to be restored.

plans with minimum effort. The methodology consists of two stages as illustrated in figure 2.

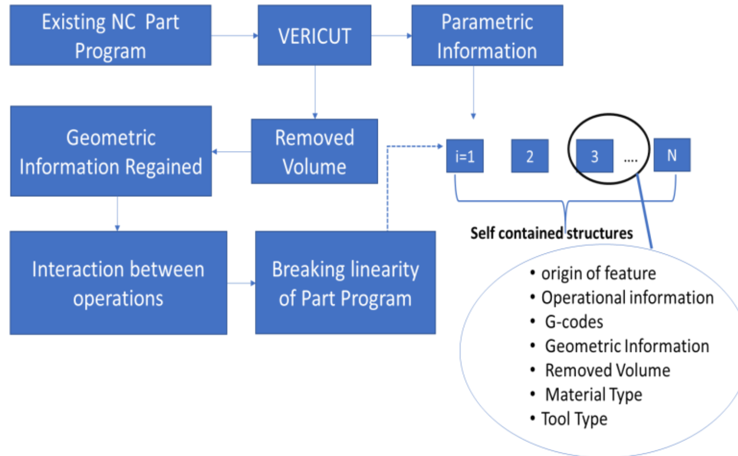


FIGURE 2: APPROACH TO MAKE OPERATIONS INDEPENDENT

3. PROBLEM FORMULATION

The processes are the combination of instructions currently available in a monolithic fashion. If a subset of operational information is required, it cannot be executed or transferred as on another machine due to the interdependency of features. NC Part programs contain information by design from CAD, and a lot of information is coming from the shop floor, which is the fundamental knowledge that the company has. This information includes tool types, operational parameters, the material removed, origin, and geometry, as depicted in figure 1. However, sometimes the adjustments are made in the part program by the shop floor worker without keeping a record of these modifications. Hence, this knowledge is procreated every time the same part is to be produced. Moreover, the data is inadequately formalized and organized because the experience knowledge of process design primarily exists in the brains of technicians/ machining supervisors. Old part programs are the asset of the company, and these act as the prerequisites to be able to perform similar operations.

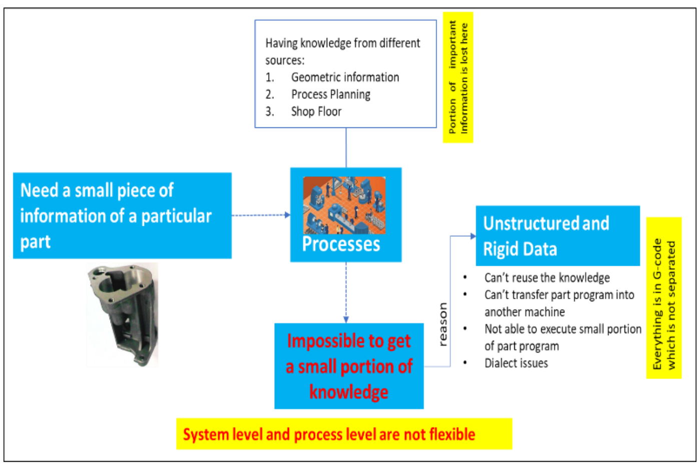


FIGURE 1: PROBLEMS DUE TO UNAVAILABILITY OF ORGANIZED DATA

Therefore, there is room for such a methodology that collects the information related to processes and creates a logical mapping between the operations. In this way, the operations become independent, and the processes are no longer rigid.

4. PROPOSED SOLUTION

The solution to the identified problem lies in standardizing the knowledge and then using this knowledge for existing and new parts. The information required for this is already distributed and available in NC part programs. This work focuses on getting the part program and extracting the useful data to identify the precedence constraints amongst the machine-able features. One of the significant advantages of this methodology is that there is no need to worry about the dialect of the machine, allowing less experienced operators capable of producing reasonable process plans with minimum effort.

4.1 Knowledge Extraction

The objective is to extract a piece of information relevant to a particular operation and making it self-sufficient to enhance the flexibility and efficiency of the processes. To do so, breaking the linearity of the part program is a way to code the knowledge. However, the geometric information of each operation and sub-operations is difficult to obtain. For this purpose, the material removed between the operations is required for the analysis of the interactions between different features of a mechanical part

4.2 Structured Information

The related process attributes obtained earlier are coded and saved as self-contained structures which helps in getting alternatives. Each structure is independent and has many facets and sub-objects, among which some facets may be connected, giving the knowledge, like the independent ones, about combining existing or new parts.

5. CASE STUDY

A case study was carried out on a real industrial part named "shimming locking support". The NC part program was obtained from an Italian startup company- Tech.Kno S.r.l. A part program contains a set of instructions and G-codes; when it is run in the simulation software, it gives the complete illustration about the line of code executing at a particular moment. In this work, part program was run in a virtual machining environment VERICUT 9.1.2 to get the required information. The operational knowledge was extracted graphically and theoretically using the same simulation software. To investigate the machining interactions between the features, the raw solid stock in VERICUT was converted into an STL model file. Subsequently, the geometry of the removed material was obtained by mesh comparison of two consecutive operations using auto-diff analysis in the software. The theoretical operational knowledge was obtained through the post-processing performed on generated APT file using a parser in MATLAB R2019b as demonstrated in figure 3. The obtained parameters are saved in a structured and organized way, acting as an independent operation.

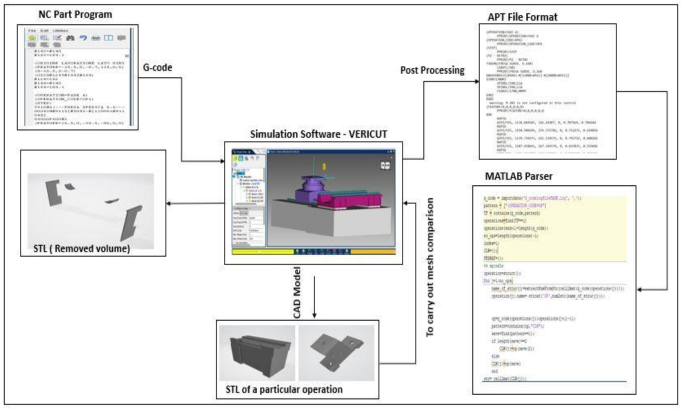


FIGURE 3: FLOW OF ACTIVITIES IN A VIRTUAL ENVIRONMENT

The application of the proposed approach is a new paradigm to improve the responsiveness of production systems at the shop floor level. Though the operational knowledge could be acquired from CAM, that would not be sufficient to give suggestions for the new part. The information available in CAM is generic, i.e., the generic shapes of cutting tools are used to simulate the operation. On the contrary, NC part programs make it possible to regain knowledge which is company-specific.

6. RESULTS AND DISCUSSION

The proposed methodology gives structured and organized knowledge related to processes. Figure 4 demonstrates the CAD model on which several machining operations were carried out. The conversion of solid CAD models into an STL model provides information about the external surface and shape of the model part. These STL model files were further used to get the volume removed between operations using VERICUT software. The parametric knowledge related to the tool has been obtained from the execution of the NC part program in VERICUT (see figure 5). The graphical analysis of the parameters obtained, can also be studied as mentioned in figure 5. Earlier, the process information was not in a single format having the dialect issues, and the operations were not independent. Using a parser on an APT file, the data has been organized in a readable and understandable format shown in figure 6.

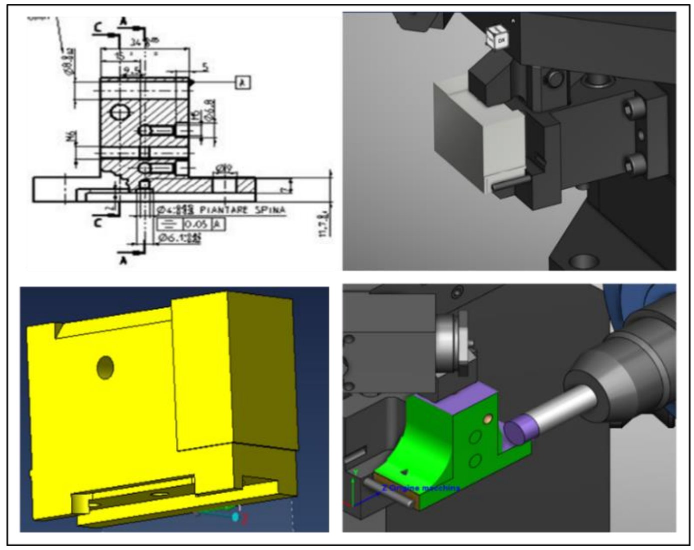
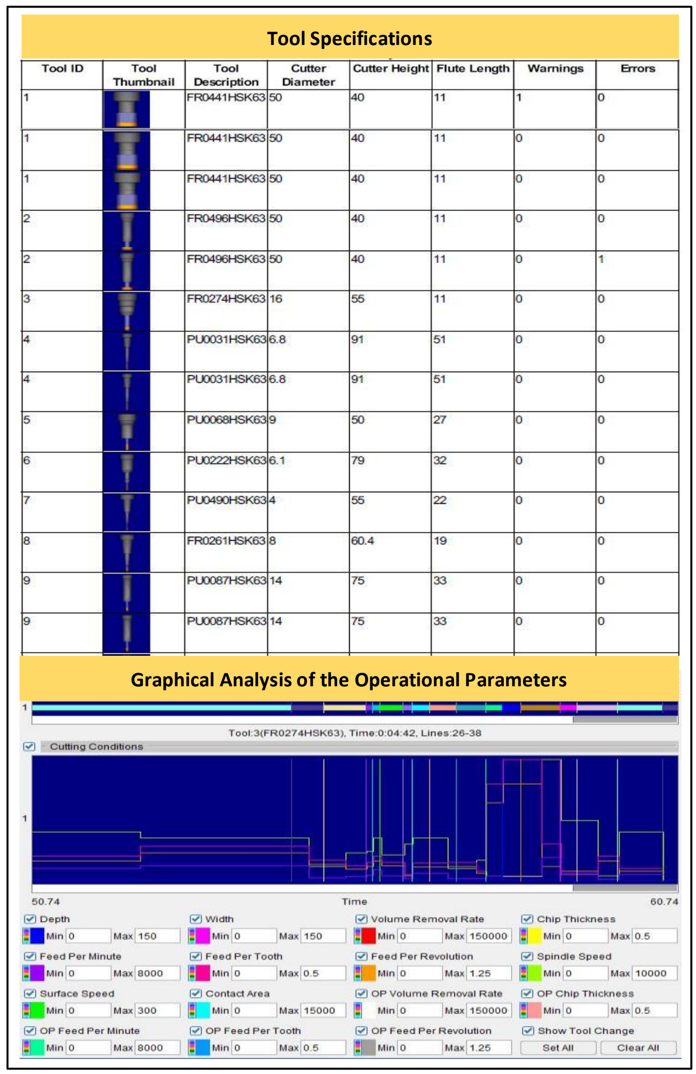


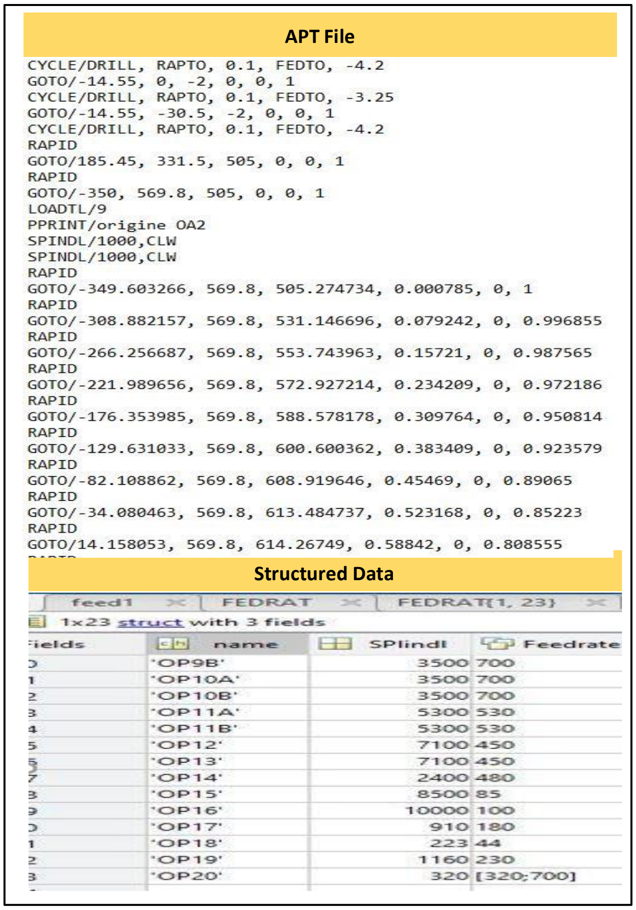
FIGURE 4: CAD MODELS OF CASE STUDY PART



Tool Specifications

Tool ID	Tool Thumbnail	Tool Description	Cutter Diameter	Cutter Height	Flute Length	Warnings	Errors
1		FR0441HSK63	50	40	11	1	0
1		FR0441HSK63	50	40	11	0	0
1		FR0441HSK63	50	40	11	0	0
2		FR0496HSK63	50	40	11	0	0
2		FR0496HSK63	50	40	11	0	1
3		FR0274HSK63	16	55	11	0	0
4		PU0031HSK63	6.8	91	51	0	0
4		PU0031HSK63	6.8	91	51	0	0
5		PU0068HSK63	9	50	27	0	0
6		PU0222HSK63	6.1	79	32	0	0
7		PU0490HSK63	4	55	22	0	0
8		FR0261HSK63	8	60.4	19	0	0
9		PU0087HSK63	14	75	33	0	0
9		PU0087HSK63	14	75	33	0	0

FIGURE 5: TOOL KNOWLEDGE EXTRACTED



APT File

```
CYCLE/DRILL, RAPTO, 0.1, FEDTO, -4.2
GOTO/-14.55, 0, -2, 0, 0, 1
CYCLE/DRILL, RAPTO, 0.1, FEDTO, -3.25
GOTO/-14.55, -30.5, -2, 0, 0, 1
CYCLE/DRILL, RAPTO, 0.1, FEDTO, -4.2
RAPID
GOTO/185.45, 331.5, 505, 0, 0, 1
RAPID
GOTO/-350, 569.8, 505, 0, 0, 1
LOADTL/9
PPRINT/origine OA2
SPINDL/1000,CLW
SPINDL/1000,CLW
RAPID
GOTO/-349.603266, 569.8, 505.274734, 0.000785, 0, 1
RAPID
GOTO/-308.882157, 569.8, 531.146696, 0.079242, 0, 0.996855
RAPID
GOTO/-266.256687, 569.8, 553.743963, 0.15721, 0, 0.987565
RAPID
GOTO/-221.989656, 569.8, 572.927214, 0.234209, 0, 0.972186
RAPID
GOTO/-176.353985, 569.8, 588.578178, 0.309764, 0, 0.950814
RAPID
GOTO/-129.631033, 569.8, 600.600362, 0.383409, 0, 0.923579
RAPID
GOTO/-82.108862, 569.8, 608.919646, 0.45469, 0, 0.89065
RAPID
GOTO/-34.080463, 569.8, 613.484737, 0.523168, 0, 0.85223
RAPID
GOTO/14.158053, 569.8, 614.26749, 0.58842, 0, 0.808555
```

Structured Data

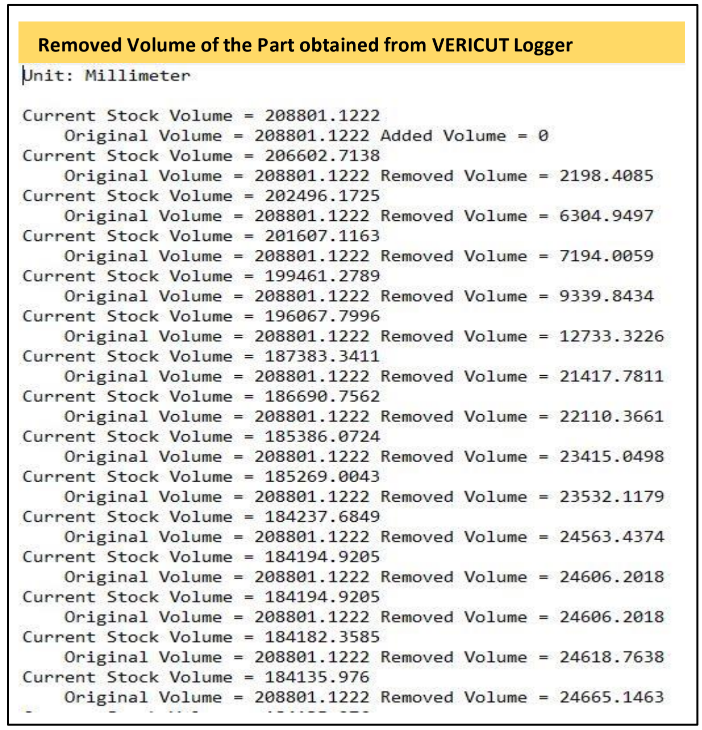
feed1 | FEDRAT | FEDRAT{1, 23}

1x23 struct with 3 fields

Fields	name	SPindl	Feedrate
0	'OP9B'	3500	700
1	'OP10A'	3500	700
2	'OP10B'	3500	700
3	'OP11A'	5300	530
4	'OP11B'	5300	530
5	'OP12'	7100	450
6	'OP13'	7100	450
7	'OP14'	2400	480
8	'OP15'	8500	85
9	'OP16'	10000	100
0	'OP17'	910	180
1	'OP18'	223	44
2	'OP19'	1160	230
3	'OP20'	320	[320;700]

FIGURE 6: KNOWLEDGE ORGANIZED IN STRUCTURES

The theoretical information of the volume removed between two consecutive operations has been shown in figure 7. To break the linearity of part programs, the interactions between the consecutive machining operations needed to be analyzed. This has been achieved by comparing the STL models in VERICUT, thus making this implicit geometric information explicit. The geometry of the material removed during the machining operations has been presented in figure 8. The reason behind converting solid CAD models into STL is that STL files are simpler and have sequential access. It does not require large amount of RAM (random-access memory) and only understands the external surface and shape of model. Although the geometric information has been regained, this would not be sufficient unless the interface of the part with outside is attained. For this purpose, the geometric data and removed material information against each operation have been saved for collision detection, which will be carried out in the future.



Removed Volume of the Part obtained from VERICUT Logger

```
Unit: Millimeter

Current Stock Volume = 208801.1222
   Original Volume = 208801.1222 Added Volume = 0
Current Stock Volume = 206602.7138
   Original Volume = 208801.1222 Removed Volume = 2198.4085
Current Stock Volume = 202496.1725
   Original Volume = 208801.1222 Removed Volume = 6304.9497
Current Stock Volume = 201607.1163
   Original Volume = 208801.1222 Removed Volume = 7194.0059
Current Stock Volume = 199461.2789
   Original Volume = 208801.1222 Removed Volume = 9339.8434
Current Stock Volume = 196067.7996
   Original Volume = 208801.1222 Removed Volume = 12733.3226
Current Stock Volume = 187383.3411
   Original Volume = 208801.1222 Removed Volume = 21417.7811
Current Stock Volume = 186690.7562
   Original Volume = 208801.1222 Removed Volume = 22110.3661
Current Stock Volume = 185386.0724
   Original Volume = 208801.1222 Removed Volume = 23415.0498
Current Stock Volume = 185269.0043
   Original Volume = 208801.1222 Removed Volume = 23532.1179
Current Stock Volume = 184237.6849
   Original Volume = 208801.1222 Removed Volume = 24563.4374
Current Stock Volume = 184194.9205
   Original Volume = 208801.1222 Removed Volume = 24606.2018
Current Stock Volume = 184194.9205
   Original Volume = 208801.1222 Removed Volume = 24606.2018
Current Stock Volume = 184182.3585
   Original Volume = 208801.1222 Removed Volume = 24618.7638
Current Stock Volume = 184135.976
   Original Volume = 208801.1222 Removed Volume = 24665.1463
```

FIGURE 7: REMOVED VOLUME BETWEEN OPERATIONS

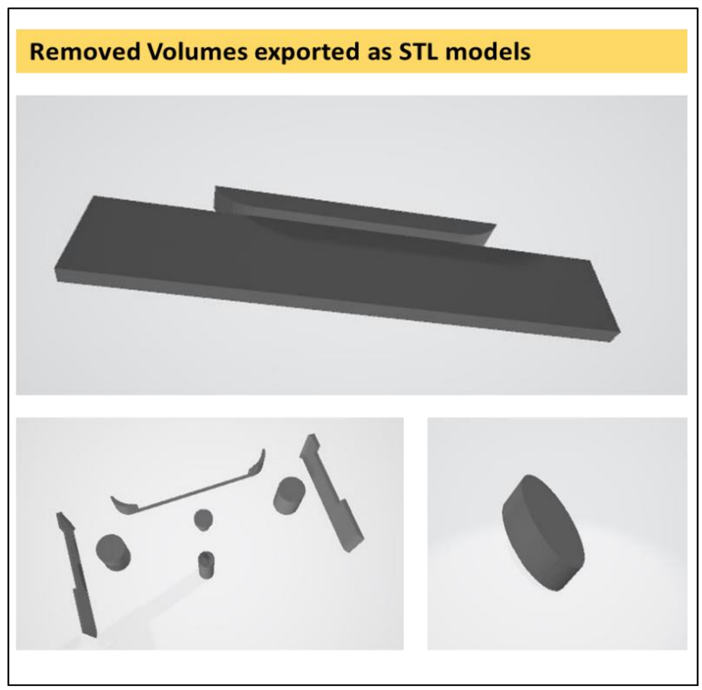


FIGURE 8: GEOMETRY OF REMOVED VOLUMES REGAINED

The proposed approach aims to obtain the relevant and valuable information of the machining operations to reuse the knowledge while performing similar operations. In this paper, a simplified approach has been explained to make part programs non-linear so that the opportunity to have alternative process plans could be available and production on different machining resources could be possible.

7. CONCLUSION

The related process attributes are extracted from NC part programs to form related independent structures. The idea is to formalize the logical and analytical knowledge for operations extracting the part information through existing part programs by simulating the operation of the virtual machine in VERICUT as per G-codes. Every operation is self-contained, and the structures of operations facilitate the change in part. Future work focuses on automating this process through a single programming script and the use of extracted knowledge to machine the parts with different resources.

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