Data Control and Management Optimization of a Flexible Manufacturing Cell through a Graph Oriented Database

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Abstract: In the constant quest to improve efficiency in product manufacturing, the implementation of database management systems (DBMS) plays a crucial role. However, challenges remain in data representation and analysis, particularly in terms of storage, which directly affects the efficiency of data processing and querying [7][13][14]. Flexible manufacturing cells and manufacturing execution systems (MES) focus on optimizing operations in work environments to ensure effective execution and improve production performance and quality of final products, depending largely on an efficient database for control, data analysis and proper management of this data flow [8][9][11]. This field of study focuses on improving data control and traceability in a flexible manufacturing cell using a graph-oriented database and visualization tools to query and understand process indicators. The following paper covers background, problem statement, objectives, scope and limitations, in addition to providing a theoretical and conceptual basis to address the challenges posed. The proposed methodology is detailed, and the expected results and necessary resources are described.

*Keywords**: Graph Database, Manufacturing Cells, Neo4j, Cypher, Manufacturing Execution Systems***

1. INTRODUCTION

The data control, monitoring and traceability project through the use of a graph-oriented database was proposed in order to implement a graph-oriented information system in a flexible manufacturing cell, specifically the one located in the Process Automation Center (CAP) of the Javeriana University of Cali, with the purpose of improving the way in which a manufacturing process is represented, due to unforeseen changes that may occur in the environment, whether the incorporation of new stations, machines or operational processes, adapting to the changing needs of the market.

Within this context of improvements in the performance and efficiency of manufacturing processes, the proposal arises to design and apply a graph-based information system that will allow precise control of the execution of the flexible manufacturing cell. This graph-based implementation strategy provides high standardization, thanks to its ability to adapt to different information models and also to the intrinsic structure of graphs to accurately represent the topology of industrial processes, allowing a deeper analysis and a clearer understanding of the operations run in a make-to-order environment [10][12] [13] [15][16][49].

At the same time, this project provides a visualization of the requests order through a report that is updated every time an order ends, allowing to have a performance record of the manufacturing cell, thus delivering a significant value to management. of production processes, opening up opportunities in data analytics and strategic decision making to guarantee more effective execution and better optimization of resources [30][31][32].

Therefore, the following article describes the design process and the results of the graph-based information system, using the CDIO methodology. Next, the tasks that were carried out in each of the previous stages will be explained.

2. THEORICAL FRAMEWORK

1. **Manufacturing Cell:** Manufacturing cells are technologies aimed at optimizing operations, eliminating activities without added value. They include machines, warehouses and robots for industrial processing. Successful implementation considers technical (design and structure) and human (operation and maintenance) aspects [17][18].

2. **MES (Manufacturing Execution System):** MES is a crucial software that manages industrial production processes, monitoring and documenting plant operations to improve the quality of the final product. It requires integration with control and supervision systems (SCADA) and ERP solutions to manage equipment and transfer production and material consumption data in real time, converting data into information for decisions [1] [19].

3. **Traceability:** Traceability is understood as the way to find and follow the trace of a product or process in each of its execution stages and identify the

conditions that surround it throughout the logistics chain and easily detect the origin of an incident [20][21].

4. **Industrial Indicators:** They primarily gauge the performance, efficiency, and effectiveness of manufacturing operations. Their analysis enables cost reduction and enhanced process performance of processes, teams, or entire companies. Furthermore, indicators quantify performance, unveil operational strengths and weaknesses, and offer valuable insights into process operation and management within theoretical frameworks [17] [18].

5. **Database:** A database is a set of related data designed to meet the information needs of an organization. It is the representation of a structured set of data, which physically contains the logical design of a set of entities of the information system that is being modeled in an organization [2] [3].

    a. **Relational Database (SQL):** Relational databases organize data into tables with columns and rows, simplifying the creation of relationships between data points. Each row represents an object with unique identifiers, stored in columns as attributes. This structure facilitates efficient storage and retrieval of related data points, forming the basis for complex data analyses within various theoretical frameworks [22] [23] [24].

    b. **Non-relational database (NoSQL):** Non-relational databases, or NoSQL, emerged in response to the need for managing massive data volumes. Unlike traditional databases, some NoSQL databases use open-source models based on the graph theory, allowing users to freely access, modify, and compile the code according to their specific requirements. This flexibility in data organization and accessibility contributes significantly to the evolving landscape of theoretical frameworks [4] [25] [26] [27] [28].

6. **Neo4j:** It is a management system for creating databases. Neo4j that allows to store the graph natively on disk and provides a framework for traversing and executing graph-based operations. The language is therefore used in hundreds of production applications across many industries vertical domains [6] [29].

7. **Cypher:** The Cypher property graph query language is an evolving language, originally designed and implemented as part of the Neo4j graph database, it is currently used by several commercial database products and researchers. A key advantage of Cypher lies in its efficiency: it materializes intermediate results solely when required, enhancing the language's suitability for complex data manipulations [6][29].

3. METHODOLOGY

As mentioned above, the methodology CDIO was used throughout this project, being a methodology from the field of engineering that provides the necessary tools to face complex problems of society in an innovative and flexible way. The stages are: Conceive, Design, Implement and Operate.

3.1 Conceive Stage

The Conceive stage involved understanding the problem and defining the requirements, through a study of the background and applications with manufacturing execution systems based on graph-oriented databases, and then defining the requirements associated with the control of the CAP manufacturing cell. Currently, the CAP manufacturing cell is made up of different machines, in which it is possible to find the following:

3.1.1 Automated Storage and Retrieval System (ASRS):

This system acts as a warehouse, where the raw materials and finished pieces that were made throughout the manufacturing cell are located. The warehouse consists of an internal Cartesian robot, which, based on a series of commands, executes the exit or entry of material. It should be noted that currently the section on the right of the machine is intended for raw materials, and the section on the other side corresponds to all the products already obtained at the end of the process. The ASRS can be visualized in the figure 1:

Figure 1: ASRS Station

3.1.2 Lathe Station:

It is a machine that takes a bar of material and makes it rotate while a cutting tool removes or shapes the material from the bar until the desired product is obtained. The material is secured and rotated by the main spindle, while the cutting tool can move along multiple axes. The types of pieces created by a CNC lathe are typically cylindrical or symmetrical around an axis. This station is made up of a CNC turning machine and a Mitsubishi robot that allows the piece to be entered or removed from the lathe. Below in the figure 2 shows the current station:

Figure 2: Lathe Station

3.1.3 Milling Station:

It consists of a CNC milling machine that is used to machine, cut and produce custom designed pieces in materials such as aluminum, iron, steel alloys, etc. It is called milling, because it is done with a tool called a “milling cutter” in the shape of blades.

Figure 3: Milling Station

3.1.4 Assembly Station:

It consists of a collaborative robot UR3 that is used to manipulate the finished pieces and carry out the checking process, where through a camera the UR3 inspects the piece to validate its final finish and finally return it to the conveyor belt.

Figure 4: Assembly Station

3.1.5 Conveyor Station:

It is used to transport the material throughout the four seasons. It has sensors that allow the activation of pistons at each station to stop the moving piece.

3.1.6 Manufacturing Cell Functional Logic**:**

The flexible manufacturing cell in the Center for Automation and Production (CAP) follows a specific sequence to complete an order. The steps involved are:

1. **Order creation:** Includes the specification of the material, quantity and type of part required.

2. **Validation of material availability**: An operator verifies the existence of the material and its location.

3. **Material transfer by ASRS**: The automatic system brings the material, without validating its content, from the raw material section to the conveyor belt.

4. **Manufacturing process:**
   a. Conveyor belt activation.
   b. Operation of the Lathe, Milling and Assembly stations.
   c. Placement of the finished part in the finished section by the ASRS.

5. **Data logging in a SQL database:** A Python script, executed by the operator, feeds the database with the data generated during the cell execution.

It is important to note that the order of these steps may vary depending on the specific characteristics of the part to be manufactured. In addition, the current structure of the manufacturing cell and its machines does not allow multiple orders to be handled simultaneously, instead, production is performed order by order, depending on the machine availability.

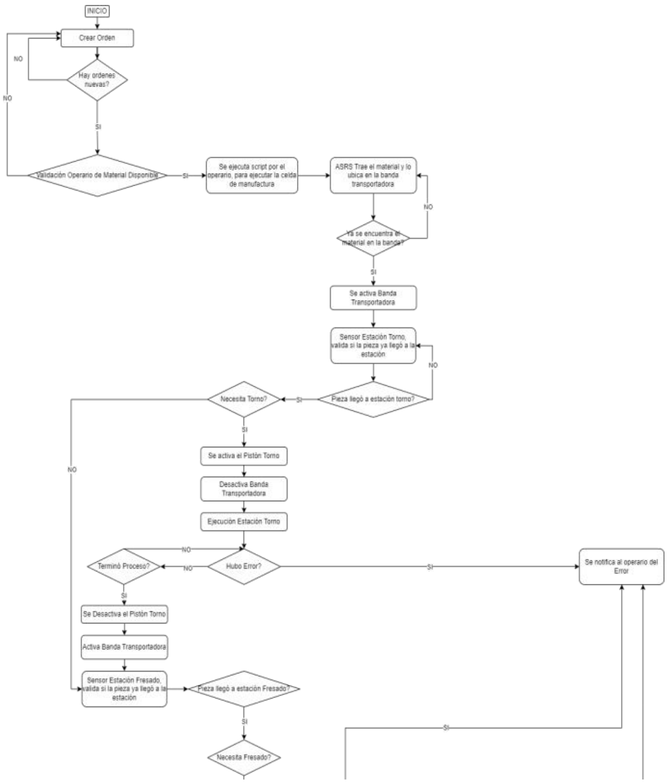

Figure 5: CAP Manufacturing Cell Functional Logic Part 1

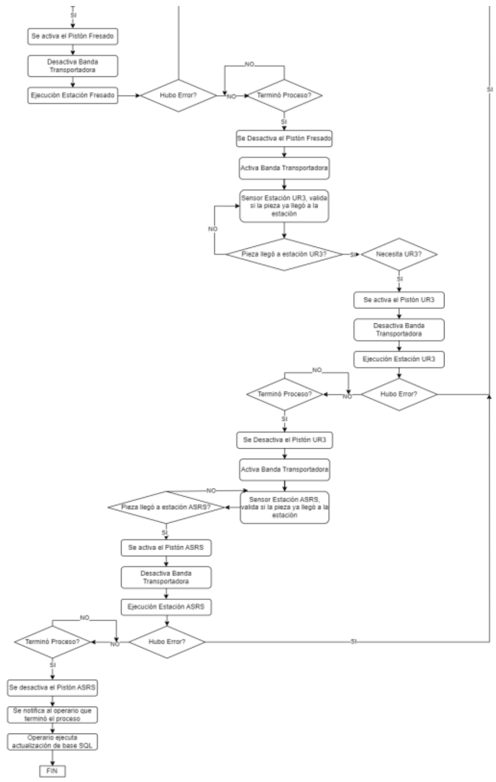

Figure 6: Manufacturing Cell Functional Logic CAP Part 2

3.2 Design Stage

At this stage, the design of the information system was carried out. To this end, four points of great importance were covered to complete the defined requirements, which are:

- Design a database that allows maintaining the logic and functional structure of the flexible manufacturing cell.
- Design a coordinator that allows controlling the physical operation of the cell, establishing communication between cell and database.
- Design a graphical user interface as a means of interaction between user and coordinator.

3.2.1 First Information System Sketch

Initially, a structural sketch was conceived that represented the elements of the manufacturing cell as nodes in the database, where the manufacturing stations, orders and orders were modeled as nodes, connected through edges that contained relevant information. These specific nodes such as Machines, Stations, Orders, Pieces, Material and System, each with their homonymous relationships. This structure is detailed in Figure 7:

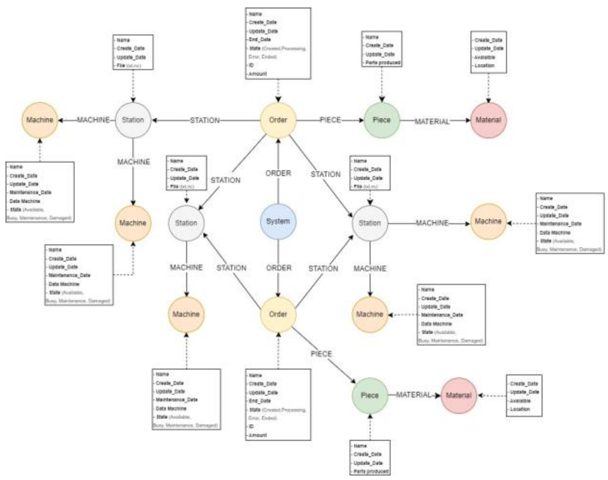

Figure 7: Database Sketch Number 1

This design allowed a clear interpretation of the physical structure of the cell and the relationships between its components, in addition to incorporating creation and update date labels to comply with key database information standards. On the other hand, the way to couple the manufacturing cell with the dashboard was analyzed, in such a way that the following points were generated to keep in mind when feeding the dashboard and being able to obtain the established indicators:

- Raw material waste
- Machine downtime.

- Active time of the machines.
- Failures and type of machine failure.

In the end, it was decided to add this information based on new relationships between the machine involved and the created order, where said relationship will save this information in JSON format or ready to access it and feed the indicators.

3.2.2 First Information System Sketch

Based on the feedback provided from the CAP experts, significant changes were implemented in the database structure, such as the elimination of the **Material** type nodes, since they only contained information about the available quantity, which it was decided to transfer to the node.

In the **Station** type nodes, two types of properties were added to manage the specific files for the Aluminum and Empack materials. This involved the incorporation of two stations (Lathe and Melling) equipped with CNC machines for specific processes depending on the material. Additionally, there are three existing piece designs, so each station now requires running three different files per material, giving a total of six files per material. This modification was reflected in the design of the second sketch of the database.

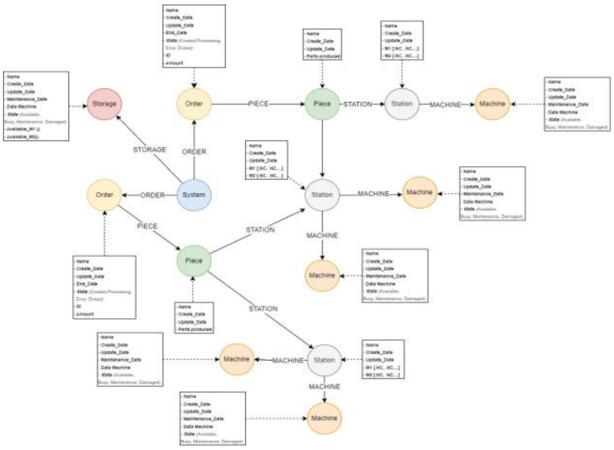

Figure 8: Database Sketch Number 2

Based on the above, observations were made to the design, which stand out:

- It is not advisable to link the address of the .NC files as a property stored in lists because this would limit the adaptability of the database to other manufacturing cell configurations with more pieces or materials in the future.

- It was recommended to devise a new sketch that reflects the functioning of the process rather than the composition of the cell where each node should represent specific tasks or steps of the process rather than physical elements of the cell.

3.2.3 Third Information System Sketch

In response to suggestions received, a new approach to database design was developed, focusing on a detailed and structured representation of the operational logic of the manufacturing cell. This approach is based on viewing the database as a sequence of essential steps and tasks, ensuring a representation that guarantees adaptability and clarity in the necessary stages of the manufacturing process of a piece with a specific material. Key modifications include:

- **Station Node:** Represents a series of stations, each composed of a set of machines, which allows the cell structure to be maintained and adaptable to different configurations.

- **Piece Nodes:** They are linked to a series of specific steps that must be executed to complete the creation of a piece.

- **New Relationship "NEXT":** Indicates the next step that must be executed to finish manufacturing the piece.

- **Elimination of the System node:** This elimination was carried out because it did not provide any relevant attributes or information for the system.

The resulting structure of the sketch is visualized in Figure 9, where various node types have been defined, such as Machines (green nodes), Stations (blue nodes), Orders (yellow nodes), Type A Steps (gray nodes), Type B Steps (red nodes), Materials (purple nodes) and Pieces (orange nodes).

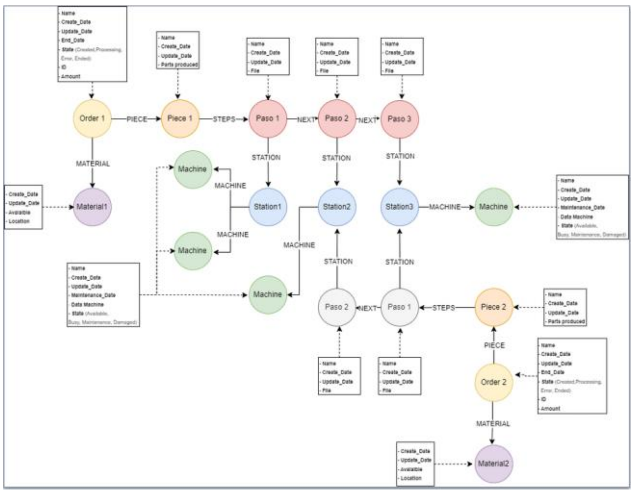

Figure 9: Database Sketch Number 3

During the design of the database, its adaptability to various manufacturing cell configurations was considered. However, complexity increases as the catalog of pieces and materials expands. This is due to the need to create (**n**) nodes with specific properties for the steps that need to be executed. Since these steps vary depending on the piece to be produced and the files are modified depending on the material of the piece, the structure becomes more complex as the diversity of products increases.

- Steps were analyzed as actions per station instead of individual tasks. This implies that some actions are performed on the same station but with different files. To manage this, the control software was used to activate the stations according to the specific order that the piece must follow, thus eliminating the consideration of files as attributes.

- The **STEP** tag now includes an attribute that indicates the step number, used to reference the station and production order of the piece.

- The **System** node was removed as it does not contain attributes or information relevant to the system.

These modifications led to design No.4 of the database, where the type nodes were defined: Machines (Purple Nodes), Stations (Orange Nodes), Order (Yellow Nodes), Material (Red Nodes), Pieces (Blue Nodes)). The above is presented in figure 10:

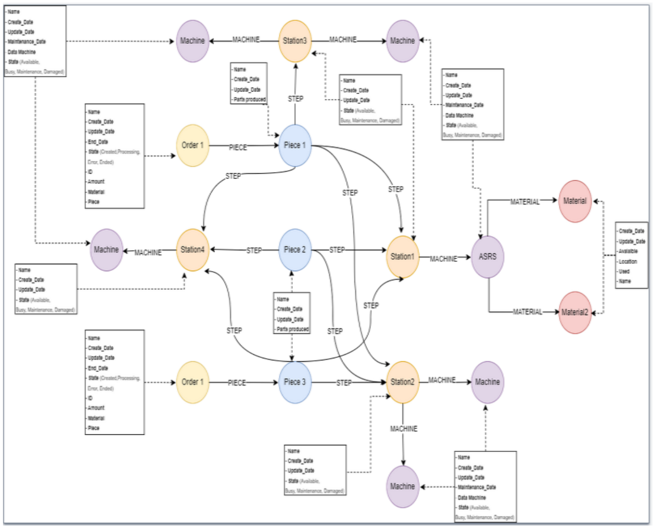

Figure 10: Database Sketch Number 3

3.2.4 GUI Development

The Graphical Interface was developed using the Tkinter and Python library. Functions were programmed for the creation, deletion, modification and visualization of orders, as well as buttons to re-establish the warehouse, activate manufacturing cell and Emergency stop. In figure 11, the graphical interface can be seen:

Figure 11: GUI in Tkinter Python

3.2.5 RoboDK simulation

Due to the current state of the machines and stations in the CAP Manufacturing Cell, performing physical testing in an ordering environment was impossible. This limitation was communicated to those involved and it was decided to opt for a simulation in RoboDK, an industrial process simulation tool. For this simulation, the following configurations were carried out:

- **Industrial Components Selection:** Specific models were chosen that replicated the CAP machines. This included a UR3 collaborative robotic arm for inspection at the assembly station, Mitsubishi RV-2FR robotic arms for turning and milling tasks and turning and milling stations equipped with Mazak Lathe and Mazak Melling machines.

- **Conveyor Belt Configuration:** A conveyor belt was implemented for the efficient movement of materials. This involved designing the conveyor belt path, developing belt speed and direction control software, and implementing infrared sensors to detect pieces and avoid collisions.

The final configuration of the simulation environment is shown in the figures 12 and 13:

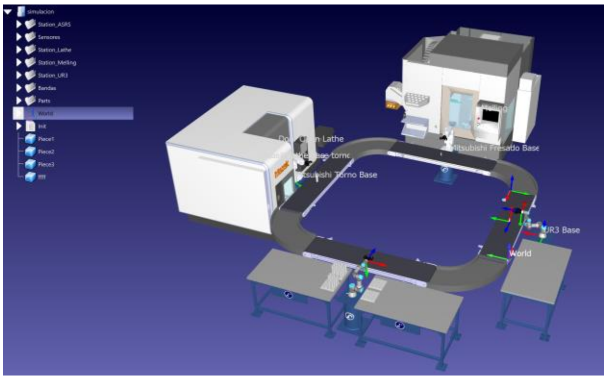

Figure 12: Manufacturing Cell in RoboDK

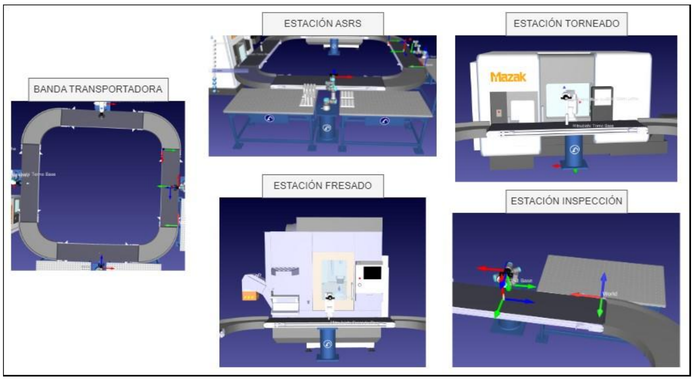

Figure 13: Stations in RoboDK

3.2.6 Control Software

For the implementation of the Control Software, it was decided to develop all the functional logic of the CAP Manufacturing Cell in a set of scripts that would allow correct execution. This functional logic allowed:

- **Independence of the Operator:** The operator will only be required to manipulate the Graphic Interface and to intervene in the stations and/or machinery when they fail.
- **Control de la Celda de Manufactura:** El software de control tiene la capacidad de activar y desactivar las máquinas a través de comunicación OPC UA, lo que permite a su vez, poder ejecutar en paralelo las estaciones.
- **Energy consumption savings:** The control software was developed in such a way that it activates the belt in sections and not completely, which reduces unnecessary energy consumption and, at the same time, belt wear.

Given this, the functional logic from the development in the Python programming code can be seen in the figure 14 and 15:

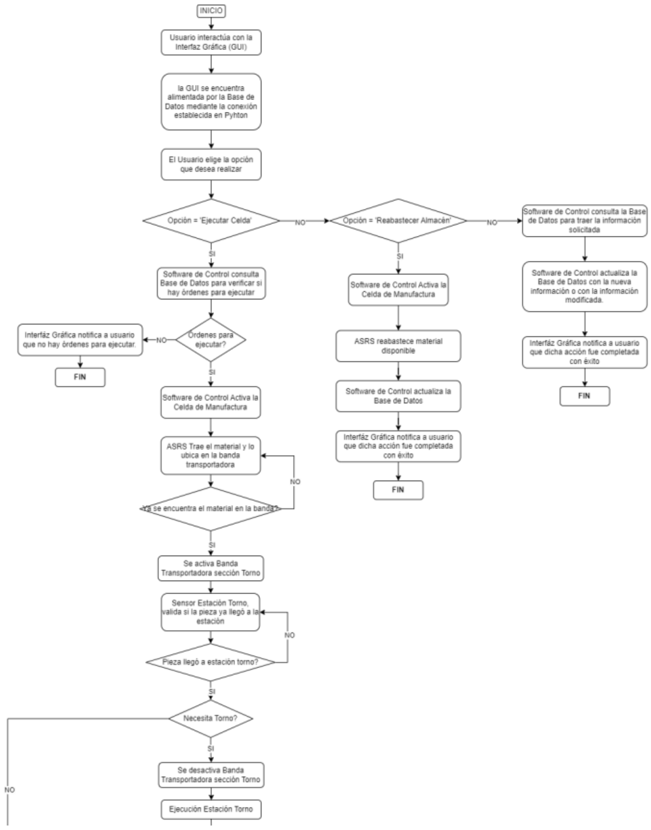

Figure 14: Control Software Functional Logic Part 1

Figure 15: Control Software Functional Logic Part 2

Since data that comes from machines represents a valuable resource in making informed decisions about production, effective management of processes and optimal utilization of machine capacity, the following indicators were identified to be monitored in order to improve the effectiveness of a Manufacturing Execution System:

- Overall Equipment Effectiveness (OEE)
- Operation Times
- Downtime
- Number of Products Produced

3.3 Implementation Stage

During the implementation stage, tests were carried out to validate the communication and connection between the different modules developed for the system, including RoboDk, the Control Software, the Database, the GUI and the Dashboard. Through various tests, the key functionalities of the system were evaluated:

- **Create Order Button Tests:** Tests were carried out to create an order, where characteristics such as material, quantity and type of piece were defined. The steps included interacting with the interface to enter the desired information and create the order. The database and Dashboard were automatically updated to reflect the changes.

- **Modify Order Button Testing:** Testing was carried out to modify an existing order, changing the piece and the quantity to be produced. After the modification, both the database and the Dashboard were updated to reflect the changes made.

- **Delete Order Button Testing**: Testing was performed to delete a specific order. Upon deleting the order, the database and Dashboard updated, showing the deletion of the order and automatically adjusting material availability and locations in the database.

- **View Orders Button Testing:** Tests were run to verify the display functionality of existing orders. By clicking on the "Orders" button, a table was displayed with detailed information of the orders present in the database, including ID, creation date, material, quantity and status.

Subsequently, the connection with the database and the Dashboard was evaluated. We resort to updating the screen, obtaining the following:

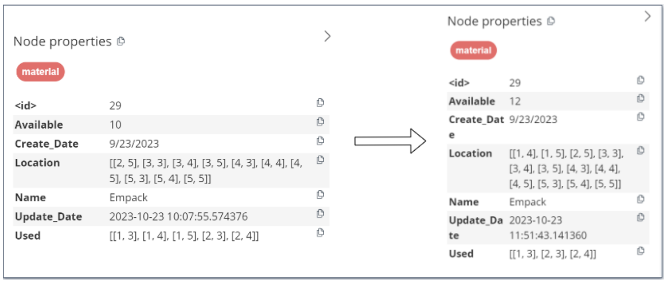

Figure 14: Empack Material Update

In figure 15, we can see that previously the order had 3 pieces to be produced, therefore, when modifying it to only one, 2 more are automatically available. In the same way, the locations where said material is found are made available again.

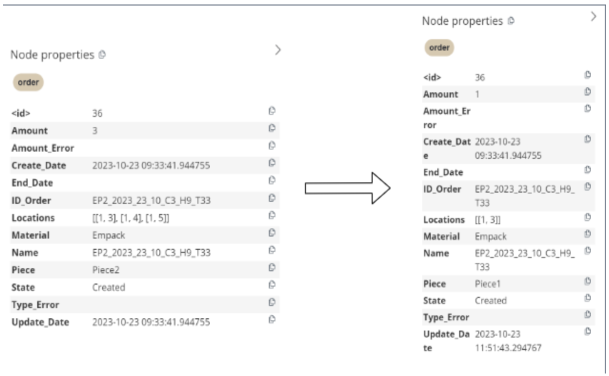

Figure 17: Update Order EP2_2023_23_10_C3_H9_T33

Regarding the update of the order **EP2_2023_23_10_C3_H9_T33**, its quantity became 1 and in the same way it is no longer expected to produce **Piece 2**, but rather **Piece 1**, which implies that in the base data the **PIECE** relation should point to **Piece 1:**

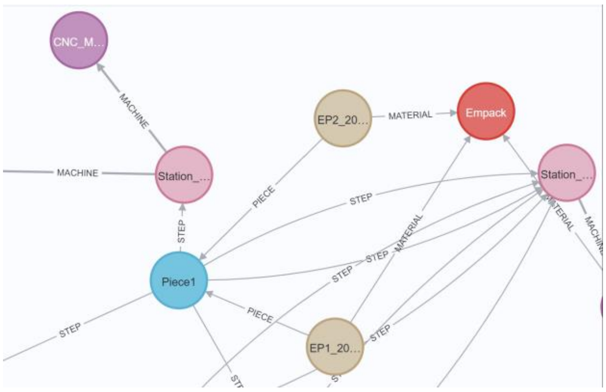

Figure 18: PIECE relationship update

4. RESULTS AND CONCLUSIONS

This degree project has successfully achieved its objectives, demonstrating the viability and ability to implement a robust and effective information system for the CAP Manufacturing Cell. Overcoming technological and operational challenges, we have developed a versatile simulation environment in RoboDK that has overcome initial limitations and provided a flexible platform to explore various configurations and conditions.

The implementation of a graph-oriented information system in a flexible manufacturing cell has proven to improve the valorization of the collected information, control and data management. The flexibility of this approach translates into a significant advantage, allowing ad hoc data and queries to be handled efficiently. This robust implementation not only improves the efficiency and effectiveness of the manufacturing process, but also reduces costs and increases the quality of the final product. It establishes a solid foundation for future research and improvements in the automation and optimization of similar manufacturing processes.

5. FUTURE JOBS

Despite the success achieved in this project, there are areas and possibilities for improvement that could be explored in future work. The key areas identified for expansion and refinement of the system are as follows:

a) **Testing in Real Environments and other MES systems:** Validating the system in real environments, including other manufacturing cells with different characteristics, will allow evaluating its performance in genuine conditions and adapting it to meet specific demands.

b) **Manufacturing Cell Investment:** Explore investments in cell infrastructure, such as Automated Warehouse System (ASRS) improvements and advanced communication technologies (IIoT, Ethernet) to improve real-time management and interconnection.

c) **User Interface (GUI) Enhancements:** Adapt the user interface to provide detailed information on the status of the manufacturing cell and prioritize orders based on criteria such as material availability and estimated times.

d) **Development of Digital Twins for the MES system:** Create digital twins to emulate the behavior of the cell, allowing advanced analysis and optimization of manufacturing processes.

e) **Implementation of Artificial Intelligence (AI) Models:** Use the data collected to develop AI models that help in predicting failures, propose preventive maintenance strategies and optimize the use of resources for inventory management, benefiting logistics efficiency and reducing costs.

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