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INTELLIGENT TOOLPATH SEQUENCE OPTIMIZATION APPROACH FOR INFINITE PRODUCTION LINES

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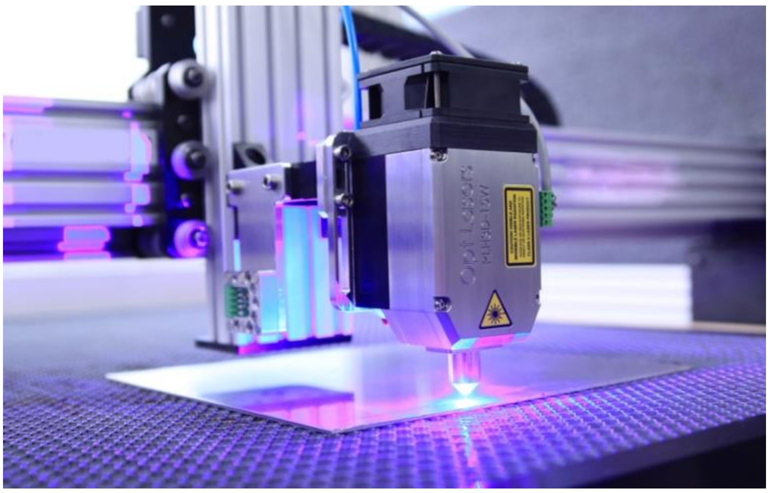

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Cover: Image related to toolpath of a CNC laser cutting machine

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Declaration of Original Work

I, Thanveer Ahammed, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Intelligent Toolpath Sequence Optimization Approach for Infinite Production Lines*", hereby, solemnly declare that this this is the original research work done by me under the supervision of Dr. Jaber Abu Qudeiri, in the College of Engineering at UAEU. This work has not previously formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Abstract

This thesis is concerned with developing a new mathematical model and software for finding the optimal toolpath for an infinite machine production line system. Existing total production time estimation for the Computer Numerical Control (CNC) machining method is solved either on a single machine or in a single operation. The combination of airtime and tool switching time consumes most of the total production time, requiring multiple operations and multiple machine production line systems. A hybrid GA technique along with a modified TSP algorithm was used to find the minimal nonproductive time in these systems. This proposed mathematical model is coded with a C++ program, and user-friendly software has been developed in this study. It was found that the total production time for multiple machining operations was significantly reduced with this technique by eliminating the unwanted cutting tool switches in the machine unit and between multiple machines. The numerical simulation conducted in this research shows that the proposed approach is feasible and practical. It is beneficial, especially in real-time manufacturing process outlines and scheduling multiple systems such as aerospace parts manufacturing, IC chip, Insertion units, job sequencing etc. by minimizing the non-productive time and thus increase the production rate.

Keywords: Optimization, Production line, CNC, Toolpath.

Title and Abstract (in Arabic)

أسلوب ذكي لتسلسل الأدوات لخطوط الإنتاج اللانهائية

الملخص

هدف هذه الأطروحة هو دراسة الدور الذي تلعبه النماذج الرياضية باستخدام المعادلات. تهتم هذه الأطروحة بتطوير نموذج وبرنامج رياضي جديد لإيجاد مسار الأدوات الأمثل لنظام خط إنتاج آلة لانهائي. يتم حل تقدير وقت الإنتاج الإجمالي الحالي لطريقة التحكم العددي بالكمبيوتر (CNC) إما على آلة واحدة أو في عملية واحدة. يستهلك الجمع بين وقت البث ووقت تبديل الأداة معظم وقت الإنتاج الإجمالي، مما يتطلب عمليات متعددة وأنظمة خطوط إنتاج ماكينات متعددة. تم استخدام تقنية GA الهجينة جنبًا إلى جنب مع خوارزمية TSP المعدلة للعثور على الحد الأدنى من الوقت غير المنتج في هذه الأنظمة. تم ترميز هذا النموذج الرياضي المقترح ببرنامج ++C، وقد تم تطوير برنامج سهل الاستخدام في هذه الدراسة. لقد وجد أن إجمالي وقت الإنتاج لعمليات التشغيل المتعددة قد تم تقليله بشكل كبير باستخدام هذه التقنية من خلال التخلص من مفاتيح أدوات القطع غير المرغوب فيها في وحدة الماكينة وبين الآلات المتعددة. تظهر المحاكاة العددية التي أجريت في هذا البحث أن المنهج المقترح عملي وعملي. إنه مفيد، لا سيما في مخططات عمليات التصنيع في الوقت الفعلي وجدولة أنظمة متعددة مثل تصنيع أجزاء الفضاء، وشريحة IC، ووحدات الإدخال، وتسلسل الوظائف، وما إلى ذلك عن طريق تقليل الوقت غير المنتج وبالتالي زيادة معدل الإنتاج.

مفاهيم البحث الرئيسية: التحسين، خط الإنتاج، CNC، Toolpath.

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Finally, I am grateful to God for letting me through all the difficulties. I have experienced your guidance day by day. I will keep on trusting you for my future.

Dedication

To my beloved parents, Ramla Badar and Badarudheen.

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List of Abbreviations

ACO	Ant Colony Optimization
AI	Artificial Intelligent
AIS	Artificial Immune Systems
AM	Additive Manufacturing
ANFIS	Adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Networks
APSO	Advanced Particle Swarm Optimization
BPNN	Back Propagation Neural Network
CAM	Computer-Aided Manufacturing
CNC	Computer Numerical Control
CTTP	Cutting Tool Travel Path
FIPS	Fully Informed Particle Swarm
GA	Genetic Algorithms
GUI	Graphical User Interface
IMPLS	Infinite Machine Production Line System
MCP	Master Cutter Path
MMPLS	Multi-Machine Production Line System
mTSP	modified Travelling Salesman Problem
NC	Numerical Control
NCP	Non-Linear Constrained Programming
NP	Nondeterministic Polynomial-time
PSO	Particle Swarm Optimization
SA	Simulated Annealing
SMPLS	Single Machine Production Lines System

sTSP	Single Travelling Salesman Problem
SVM	Support Vector Machines
TSP	Travelling Salesman Problem

Chapter 1: Introduction

1.1 Overview

Over the years, advanced manufacturing has become an extremely refined process. The key factor that makes the widespread popularity of Computer Numerical Control (CNC) machines in the entire manufacturing industry is their ability to reduce human errors and improve production efficiency. Intelligent CNC technologies can effectively produce a wide range of complex products with pre-programmed computer software that defines the movement of machine tools and equipment. CNC machining can be done with almost any complex structure with minimum effort.

A production line in a factory is a set of manufacturing machines that move the workpiece from one machine to the next until they are converted into a finished product. Each machine will be capable of doing a specific set of operations, and those operations will be carried out using certain programming codes. The intervention of advanced CNC machines into the smart manufacturing production line system received more acceptance due to the key advantages, including high machining accuracy through simple programming and repeatability in complex parts machining [1], [2].

In the aerospace, automobile, electronic semiconductors, circuit boards, and biomedical industries, the most significant machining processes are hole-making and milling operations with different dimensions. Thousands of machining operations may be required for the assembly of each structure. The precision and efficiency of machining are directly influenced by the quality of the Numerical Control (NC) toolpath. Typically, CNC machining centers carry out machining operations following instructions provided by a CNC programmer. So, the optimal processing for NC programming or toolpath selection relies upon the programmer's experience and the data from the machining handbooks. This traditional NC programming method has various drawbacks compared to modern CNC machining, including higher time requirements for programming, high production costs, lower accuracy, and increased production time.

To overcome these limitations, various advanced manufacturing simulation software is introduced into the market. Using inbuilt NC programming methods and artificial intelligence optimization tools, this simulation software can save the waste of time, materials, and costs as well. The toolpath selection is one of the most important aspects of improving the machining process. Researchers have used several Artificial Intelligent (AI) approaches or hybrid methods for toolpath optimization. Regression-based AI modelling such as ANN and AI optimization techniques such as Genetic Algorithms (GA), Artificial Immune Systems (AIS), Ant Colony Optimization (ACO), and Particle Swarm Optimization (PSO).

In several industries, GA is utilized to resolve sequence optimization problems in CNC drilling [3]. For real-time optimum control, a modified ANN was applied to the milling system [4]. The application of AIS will reflect the efficacy and capability of AI on the toolpath optimization system's performance [5]. The ACO algorithm proved useful in determining the best path for a three-axis CNC drilling machine [6]. The PSO scheme is adopted to generate a set of cutter locations that reduces error on the CNC machined surface [7]. In comparison to other hybrid techniques, GA has been claimed to have been effectively adopted by most researchers for toolpath issue optimization [8]. GA can also be used to determine the optimum sequence of operations for a group of processes that are in asymmetrical locations and at different levels [9].

The Traveling Salesman Problem (TSP) is a well-known and most-studied combinatorial optimization problem. This kind of problem is termed a Nondeterministic Polynomial-time (NP) hard problem [10]. When GA is combined with TSP for toolpath optimization during drilling, the overall machining time is reduced by approximately half [11]. But the existing toolpath optimization problem was typically solved for a single machine and a specific type of operation. To the best of the author's knowledge, the optimization of toolpath sequences for multiple operations at a single point and between multiple machines is still not solved in previous literature.

So, the optimization of toolpath sequences for multiple operations at a single point and between multiple machines is a significant problem facing the manufacturing industry. This issue is addressed, and a practical solution is developed through this project.

1.2 Statement of the Problem

Most of the complex products require a combination of different processes such as center drilling, reaming, countersink, counterboring, milling, and other operation like grooving, etc. In the aerospace and automobile components manufacturing industry, multiple sets of machining processes will be required at a single point on the workpiece. Similarly, in pocket milling operations (rough cutting followed by fish cutting), this can be achieved either by the same or different cutting tools. Usually, these sets of operations are followed by a certain order/constraints. Here, the total production time directly depends on productive time and non-productive time. The major share of non-productive time is used by the airtime and tool switching time. Airtime is defined as the time required for the cutting tool to move from one point to another to initiate the next operation without having any contact with the workpiece. The route through space that guides a cutting tool's tip on its way to making the desired geometry on the workpiece is called its toolpath. The tool switch time refers to the time required for changing the cutting tool for performing each operation. Therefore, the sequence of cutting tools selection and its toolpath will directly affect the overall production time.

In a production line system, multiple machines were arranged in serial or parallel layout to perform a set of machining operations on the workpiece without interrupting production flow. Each of these machines can perform a certain set of operations by changing its cutting tool. The workpiece will transfer from one machine to the next by a conveyor until the end product is obtained. Intermediate and final products are processed in a specified order on machinery in any manufacturing plant. So, the optimal toolpath should be identified with minimal tool switches within a single machine and between multiple machines.

The sequence of operations used to convert a raw workpiece from scratch to the final product is referred to as its path. For example, consider a product that requires four sets of operations in a production line. Here, five machines are named Machine 1, Machine 2, Machine 3, Machine 4 and Machine 5, all of these machines are arranged in a series layout except Machine 3 and Machine 4 which are in parallel. The first operation set can be done in Machine 1 and set two operations by Machine 2. There are two options for the third set operation: either can be done in Machine 3 or Machine 4, depending on the machine used for the third operation set. Then the workpiece will be sent to Machine 5. Machines 1-2-3-5 are on ‘Path 1’ while Machines 1-2-4-5 are on ‘Path 2’. This concept is illustrated below in Figure 1.

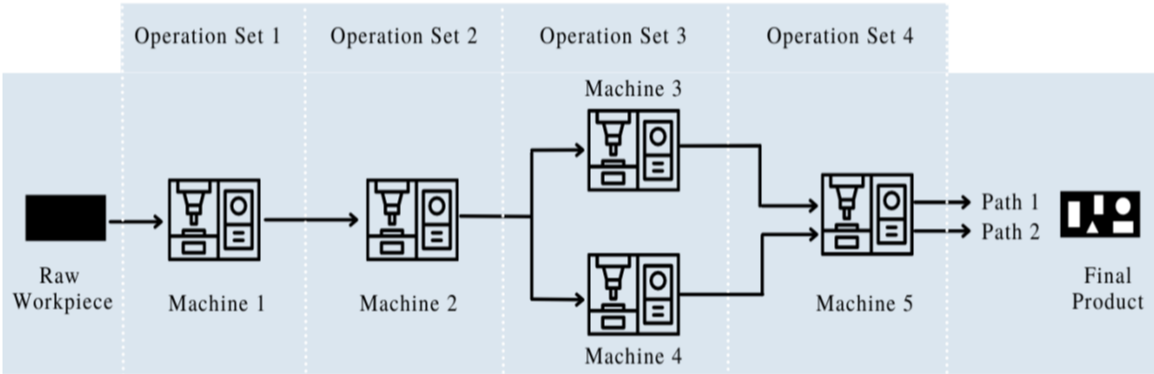

Figure 1: Illustration to demonstrate the workflow path in a 5M production line

The possible ways to complete the entire process are:

1. Complete all the processes in the same location on the workpiece by changing the possible tools and then move to the next machining location. But this may raise unnecessary tool switches and consequently extends the tool switch time.
2. Perform all processes which require the same cutting tool in use and replace the tool after its possible processes. This will result in a decrease in tool switching time. However, it may increase tool airtime [12].
3. Finish all the possible precedent processes in machine 1 and transfer the workpiece to machine 2 for the remaining processes to avoid unnecessary tool switches in machine 1.

In this research, optimization of toolpath sequences for multiple operations at a single point and between multiple machines in the production line are addressed, and a practical solution is developed.

1.3 Research Objectives

This research aims to specify and find the solution that generates the optimal process sequence in a production line system by minimizing the non-productive machining time. An efficient AI-assisted machine toolpath optimization technique is needed to find the optimal non-productive time. From the literature analysis, a combination of GA and TSP shows significant results for a similar scenario. A modified TSP should be developed for this complex problem while the traditional TSP cannot. The optimal process plan developed in this context is expected to deliver an optimal toolpath sequence by minimizing the airtime and tool switching time for various complex workpieces. Here, we need to develop a new customized method that can find optimal sequences in a single machine and infinite production line systems. An advanced GA with a modified mTSP optimization technique will be used to find the optimal toolpath sequence. Also, needed to develop open-source software with a user-friendly Graphic User Interface (GUI) based on this technique.

1.4 Thesis Structure

The following section will cover the framework of the research, which is followed by a literature review of the existing optimization methods for generating toolpaths in Chapter 2. Chapter 3 will discuss the theoretical framework for the models and mathematical models used to develop a prototype solution to the research problem. This is followed by a set of test cases designed to validate the developed prototype in Chapter 4, with the results of these test cases provided in Chapter 5. Conclusions of the research are provided in Chapter 6. Also, a discussion about the area of implementing this technique is discussed and the scope of future research is discussed in Chapter 7. An outline of the thesis structure can be seen in Figure 2.

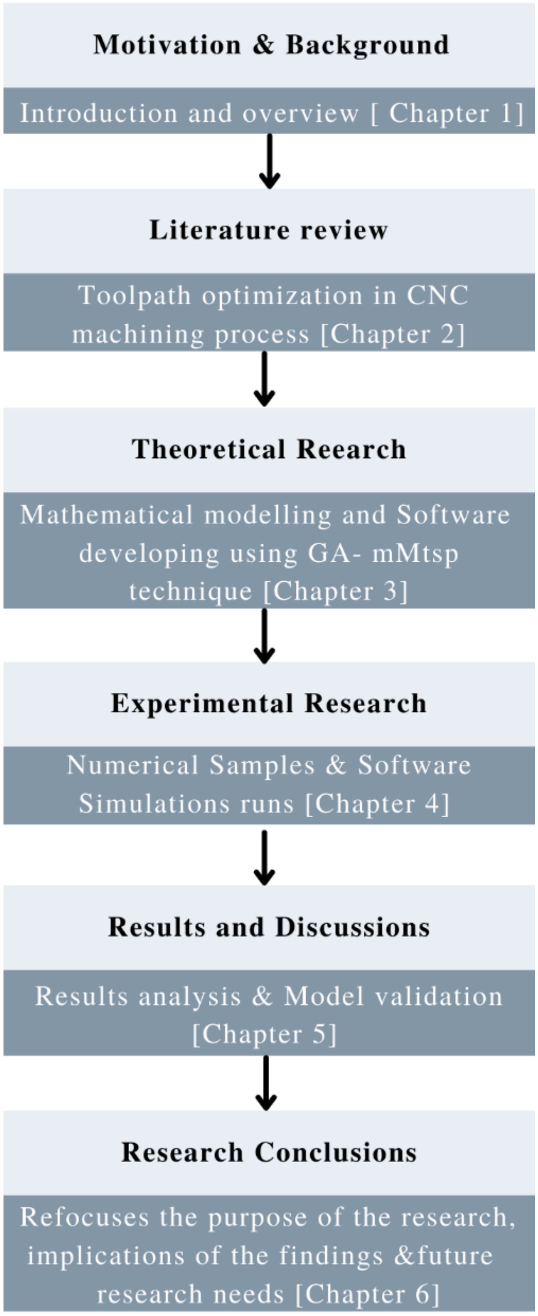

Figure 2: Framework of the thesis

The layout of this report is arranged based on the above-illustrated framework and the next chapter will discuss about literature review.

Chapter 2: Literature Review

2.1 Previous Research Works

Many research works have been conducted on the AI-assisted machine toolpath optimization techniques, which majority of which employ ANN, GA, ACO, PSO, and AIS optimization methods. Chen and Tseng [13] utilized GA to plan near optimum toolpath and workpiece location to reduce the processing time needed for a robot to complete the task. GA generated plans were found to have better efficiency in minimizing processing time compared to human-generated plans. GA was also implemented to determine optimum cutting parameters for machining prismatic parts [14]. This powerful AI tool yielded a high-performance optimization system which helped to improve productivity and competitiveness. Castelino et al. [15] developed an algorithm intended to minimize the non-production time or airtime in a milling operation by connecting diverse toolpath segments optimally. The minimization problem was formulated as a travelling salesman problem with precedence constraints. The heuristic algorithm developed could give optimum solutions in the process planning system, and it outperforms random solutions and local search methods significantly. The airtime savings were evident when the problem size increased. This approach can be applied not only to machining operations but also to path optimization problems involving numerous constraints in advanced manufacturing operations like laser cutting and fused deposition modelling. Thus, GA can be effectively integrated online with an intelligent manufacturing system for automated process planning, to reduce production time and cost, and enhance product quality and flexibility in cutting parameter selection [16].

For machining free form surfaces, iso-scallop machining is considered the efficient machining strategy as it yields better surface roughness and minimizes machining time compared to other methodologies. Agrawal et al. [17] demonstrated that the machining time of iso scallop machining can be reduced by optimizing the orientation of the principal or Master Cutter Path (MCP) through GA implementation. This technique significantly reduces overall machining time compared to conventional cutter path generating methodologies. Oysu and Bingul [18] applied heuristic algorithms such as Simulated Annealing (SA), Genetic Algorithm (GA) and a hybrid algorithm (hybrid-GASA) in toolpath optimization problems to reduce airtime. These algorithms were tested during the milling process of wood materials in the three-axis cartesian robot. A comparison was carried out between these algorithms based on minimum toolpath and airtime. Hybrid – GASA reached near-optimal solutions earlier than single approaches, demonstrating better efficiency. The combined global search feature of GA and the local search feature of SA helped to achieve a 47% better minimal path solution than SA alone.

However, the improvement over standard GA was 1.5%. The effectiveness of the approaches was compared based on less airtime and minimum tool travel path. Hybrid algorithms demonstrated better effectiveness than other heuristic approaches. GA was incorporated with Travelling Salesman Problem (TSP) to find the optimum sequence of operation for machining at asymmetrical locations and varied levels [9]. The shortest Cutting Tool Travel Path (CTTP) was attained, and GA with TSP application was suggested for other manufacturing operations like spot welding. This can also be incorporated into commercial CAD/CAM software for attaining the best CTTP during the generation of programs. The effectiveness of GA in handling complex optimization problems was illustrated in [19]. Machining parameters of milling operation were optimized to achieve minimum machining time, cutting force, better tool life, surface characteristics, and overall efficiency. Good agreement between the GA provided values and measured values show the potential of GA. Optimized values could provide superior surface finish and productivity. GA was further utilized for efficiently optimizing machining parameters in turning operations [20]. The objective function was to achieve the shortest machining time, with constraints like cutting force and power, surface finish, tool life, and range of turning parameters. GA can also be adopted in the tangential turn-milling process, in which the workpiece and tool rotate simultaneously. Machining parameters of the turn-milling process were optimized to achieve the least possible surface roughness by the GA approach [21]. Optimization of the toolpath in the drilling operation is also so important since it yields higher productivity with less production cost, particularly in the drilling of numerous holes at different locations. Pezer [10] applied GA to optimize the drilling toolpath by converting the optimization problem to TSP. It was carried out in MATLAB software, and the output was compared with that obtained from CAM packages. GA provided more favorable solutions that were closer to the optimum. GA helped to reach the optimum solution in a relatively short time too. Nowadays, robotic systems are being used to perform drilling operations. Optimizing the drilling sequence in robotic system assisted drilling is also crucial in achieving the best performance. Dahmane et al. [24] developed a GA-based optimization technique to shorten the machining time of drilling several holes using three axes robot. The approach was found to be effective, and it did not degrade the precision movement of the robotic system. Kumar and Khatak [23] developed a discretized model for optimizing the toolpath in milling operations, using GA. The output depicted the effectiveness of the methodology in optimizing the toolpath based on various objective functions.

Artificial Neural Networks (ANN) provide an efficient and rapid selection of optimized parameters through the processing of available technical data. Zuperl and Cus [24] proposed a neural network approach to optimize multiple objective problems in the machining process. This approach is usually used for the fast determination of optimized machine conditions, where deep analysis consumes more time. Turning process parameters were optimized using the approach, and validation has proven improved performance. The study also suggested applying this approach to other machining processes like milling, drilling, grinding, and so on. Characteristics such as robustness, fast processing, lower memory consumption, and the possibility of self-learning make the approach feasible for effectively optimizing machining parameters in real-time, they developed a new hybrid optimization technique for complex non-linear optimization of machining parameters [25]. Maximum production rate with minimum cost must be achieved with desirable machining parameters without disrupting the required cutting constraints. The analytical program TIS was used along with ANN for the optimization. OPTIS is capable to select optimum machining conditions from a commercial database, to reduce the cost of production. A satisfactory agreement between low cost and high productivity can be reached by the selection of optimized parameters. The hybrid algorithm developed provides higher precision in predicting the results and is very efficient in Non-linear Constrained Programming Problems (NCP). It also performed better than genetic algorithms and programming approaches in terms of objective function values. Li et al. [26] designed a neural network-based multi-objective optimization approach to optimize the process parameters in sculptured parts machining. The Back Propagation Neural Network (BPNN) model was proposed to forecast machining parameters to minimize machining time, energy consumption, and surface roughness. When compared to conventional methodologies, this model showed better effectiveness upon validation. Fok et al. [27] also employed ANN to create an optimum toolpath by building multi-destination paths that allow the cutting tool to reach all the spots in a timely way.

Artificial Immune Systems (AIS) are just another effective artificial intelligence technology. Ülker et al. [5] utilized AIS in combination with a Non-Uniform Rational B-Spline (NURBS) mathematical model to minimize machining time and improve efficiency while cutting sculptured surfaces. The method was implemented in the programming language C and may be included as a CNC machine tool module. The model's performance indicated the capability of AI approaches for improving machining parameters. AIS was used in the optimization of milling parameters to achieve better surface integrity in the milling process of the Ti-6Al-4V alloy workpiece [28]. Different parameters like speed, feed, and depth of cut were predicted for reducing surface roughness. AIS delivered the optimal cutting conditions, resulting in the least amount of surface roughness. The experimental and predicted values were in good agreement.

Ant Colony Optimization (ACO) has also been employed by several researchers to solve different combinatorial optimization problems. This population-based optimization was used to optimize the hole-making process by Ghaiebi and Solimanpur [12]. They successfully minimized the tool travel and tool switch times of hole making process in which each hole needed multiple tools to complete the task. Ant algorithm developed was tested and found to be effective in determining optimum sequence. It can also be applied to optimization problems in other manufacturing operations with technical constraints. Modified ant colony algorithms have also been proposed for addressing multi-pass optimization problems, to identify processing parameters with the lowest production cost possible, subject to a set of machining constraints [29]. Cus et al. [30] employed an Adaptive Neuro-Fuzzy Inference System (ANFIS) system to represent the manufacturer's objective function and ACO to identify the most suitable objective value while optimizing turning process parameters. It can generate a near-optimal solution in a very vast solution space in a reasonable amount of time. The hybrid approach proposed can also be used for other machining tasks such as milling operations. The ACO method was used to complete toolpath optimization for drilling operations involving large rectangular matrices of holes [31]. Since commercial CAD software does not always give fully optimized paths through their generated plans, TSP with ACO algorithm can be efficiently used to achieve large reductions in toolpath travel time. Parallel implementation of ACO was done to determine an ideal sequence of G-codes for hole cutting operations on printed circuit boards to have the shortest toolpath [32]. The availability of low-cost parallel ACO architecture has spurred research interest in parallel ACO. The travel route was designed as an application of TSP. The combination of a Parallel ACO algorithm and TSP method may be used in any analogous application, such as welding and tapping.

PSO is an approach that is not only simple but also works exceptionally well in a wide range of test situations. Onwubolu and Clerc [33] proposed a novel method for reducing the tool travel path in CNC drilling operations. First, the operational route is specified as a TSP. Then it can be solved using the novel heuristic, particle swarm optimization technique. PSO requires only minimal control variables and is easily adaptable, resilient, and simple to use, thus leading to decreased production costs. PSO was used to efficiently optimize machining parameters in milling processes where multiple conflicting objectives were present [34]. ANN predictive model was used to predict cutting forces and then the PSO algorithm was used to obtain optimum cutting speed and feed rates. The results show that this integrated system is a powerful tool for tackling multi-objective optimization problems. The system's outstanding precision over a wide range of machining parameters suggests that it can be used in several manufacturing industries. PSO can be an effective optimization technique for nonlinear continuous optimization, combinatorial optimization, and mixed-integer nonlinear optimization problems [35]. PSO was also used to optimize the parameters of the turning process [36]. An example demonstrates that optimum cutting parameters are easier to satisfy the optimizing object than empirical ones, and PSO may be used to solve complex nonlinear problems. Prakasvudhisarn et al. [37] introduced a PSO-based approach to optimize CNC end milling parameters to attain a desired surface roughness level. To capture roughness features and related components, a machine learning approach known as Support Vector Machines (SVMs) is proposed. Next, they are incorporated into an optimization problem so that PSO can be applied to find optimum process parameters. The collaboration of both approaches can produce the appropriate surface roughness while also maximizing productivity. PSO was used to select optimum machining parameters to minimize unit production cost in multi-pass turning by Srinivas et al. [38]. Hsieh and Chu [39] investigated the optimization of toolpath planning in 5-axis flank milling of ruled surfaces using advanced PSO algorithms, with machining error as the objective. To increase the quality of optimum solutions, the Advanced Particle Swarm Optimization (APSO) and Fully Informed Particle Swarm Optimization (FIPS) algorithms are used. The results of the tests demonstrated that FIPS is the most effective in minimizing error across all trials, whereas PSO works best when the number of cutter positions is relatively small. This study enhances toolpath planning in 5-axis flank milling by reducing machining errors. Automatic programming of CNC milling machines was also done using PSO, which leads to minimized manufacturing time and production cost [40].

From the literature review analysis, few gaps were found, and these gaps are addressed in this research.

2.2 Literature Gap

Some of the key literature gaps are identified and discussed below:

- Existing CNC time estimation methods are based either on a Single machine or Single operation.
- As current methods don't illustrate the necessity of multiple operations with more than one machine.
- Most of the production job sequencing is manually controlled.
- Inadequate optimization options in CAD/CAM software for complex job sequencing.

These key problems are considered for conducting this thesis work.

Chapter 3: Research Design

The integrated GA-TSP technique can accomplish toolpath optimization by minimizing the airtime of cutting tools in a production line. According to the proposed technique, the GA with certain constraints is used with a set of parameters. But traditional TSP cannot be applied to our toolpath problem due to some limitations. So, the existing TSP problem is modified to solve toolpath path optimization issues for complex structures. The following section will discuss the modification in traditional TSP for solving the context of having complex machining sequences in an infinite production line.

3.1 Modified mTSP for a Complex Trip

In Traditional TSP / single TSP (sTSP), it works on the principle that there will be one salesman and ‘n’ cities, where each city is defined by its own location or coordinate points. The objective is to find the best trip with minimum cost. If we adopt this technique to the toolpath optimization problem, the cutting tool will be the salesman, and the cities will be the machining process location on the workpiece. Since each machining process is defined by its location, the tool will visit each location once.

However, with mTSP, there are ‘m’ number of salesmen. Each of them visits a certain set of cities, ensuring that all cities are visited. The optimal trip duration will be found by adding the shortest distance travelled by each salesman. Here we adopt the modified mTSP technique to find the optimal toolpath sequence in a manufacturing production line system. So, the following criteria should be considered in the production line system.

- There will be an “m” number of cutting tools in each machine unit. i.e., “m” number of salesmen will be assigned in this case study.
- Each machining location will be assigned as one city, which is defined by its coordinate points on the workpiece.
- In traditional TSP / sTSP, each city needs to be visited exactly once by the salesman. While in this proposed problem, each city may need to be visited multiple times. For example, in some cases, drilling, center drill and tapping may be executed in the

same location. So, the cutting should revisit the machining location more than one time.

- The Salesman or the cutting tool can depart from any location and return to their respective location based on the operation sheet given by the user.
- The tool switching location for each machine unit will be defined at the beginning of the simulation.
- The optimal toolpath sequence for the production line will be the sum of individual optimal sequences in each machine unit.

This modified mTSP is solved by the renowned hybrid GA technique and developed a predictive toolpath sequence optimizing simulator for a CNC production line system.

3.2 Proposed GA for Infinite Production Lines

As discussed earlier, a hybrid GA is implemented to solve the modified mTSP. GA is implemented for finding the best fitness among the generated populations. New populations are generated by GA based on each solution, which is known as individuals, for initial solutions by employing the methods called crossover, mutation, etc. [41].

The genetic algorithm consists of the following steps:

- Creating the base population.
- Individual evaluation.
- Individual selection.
- Crossover.
- Mutation.

In this study, GA is utilized to find the optimal toolpath. This can be done by finding the optimal sequence of operation that achieves the shortest toolpath. The GA begins with the encoding operations. The set of operations are represented according to their coordinates, and they are listed in the order by which the tool visited each location. The problem can be coded as follows:

Individual = $[(xi, yi, zi),(xj, yj, zj), \ldots, (xn, yn, zn)]$

Where the first gene (xi, yi, zi) represents the location of the first operation. Permutation encoding is used to solve a string of characters or numbers, which is implemented to solve the TSP. Different phases of standard phases in GA are shown in Figure 3.

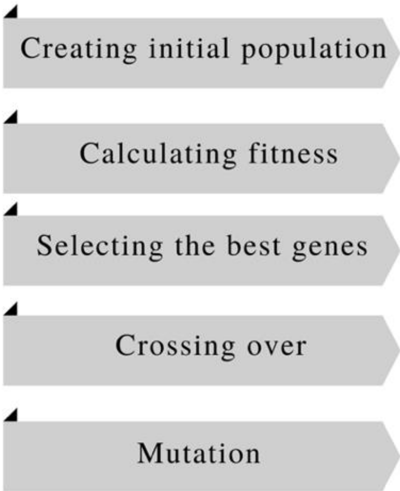

Figure 3: Standard 5 phases in genetic algorithm

3.2.1 GA Parameters

The genetic information of two parents can be combined to generate new offspring by using the crossover method. The greedy crossover is utilized because each operation should have resembled once in the individual [42].

For solving GA, we need to define some parameters. For example, consider there are 6 cities. Greedy's crossover method and swap mutations are illustrated in Figure 4 and Figure 5 respectively.

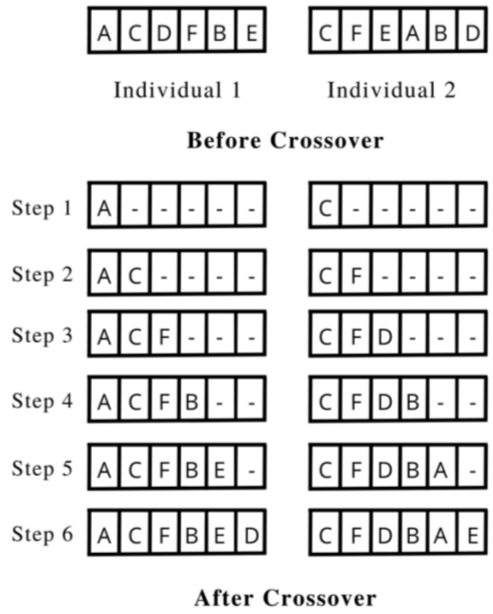

Figure 4: Greedy crossover method

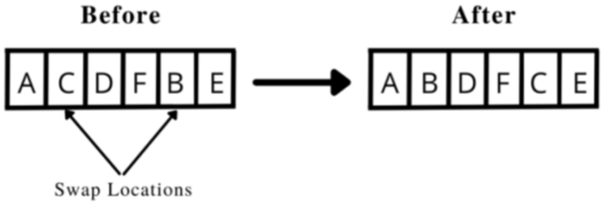

Figure 5: Swap mutation

The mutation operator for GA is implemented by choosing two genes from the provided individuals and the genes are swapped. The crossover and Mutation rates are 0.75 and 0.03 respectively employed in this study.

3.3 Hybrid GA - mTSP Algorithm

A hybrid GA- mTSP Algorithm was used to develop the optimization software. Various steps involved in the algorithm are described below:

Step 1: Create the operation sheet which defines, the number of cutting tools, machines, machining locations etc.

Step 2: Upload the operation sheet into the developed computational program model.

Step 3: Define cutting parameters, tool switching location, tool switching time etc.

Step 4: Selection of the closest machining location for the cutting tool which is defined in the operation sheet.

Step 5: Computing the nearest location assigned to that cutting tool is unvisited and moves there.

Step 6: If there is any location left unvisited, check whether any other cutting tool is assigned to visit that location. If there is any, calculate the time for covering that distance and compare it with the time that will be taken to hand over the duty to another assigned cutting tool. If the time for covering that distance is less, repeat step 4.

Step 7: Repeat these steps for 5000 iterations, if there is any shortest distance calculated between these iterations, the new path will be selected, and the iteration continues. If there are no changes occur, the optimal sequence will be generated.

An integration of GA and TSP should be applied in this algorithm. The flow chart for hybrid GA-TSP is illustrated in Figure 6.

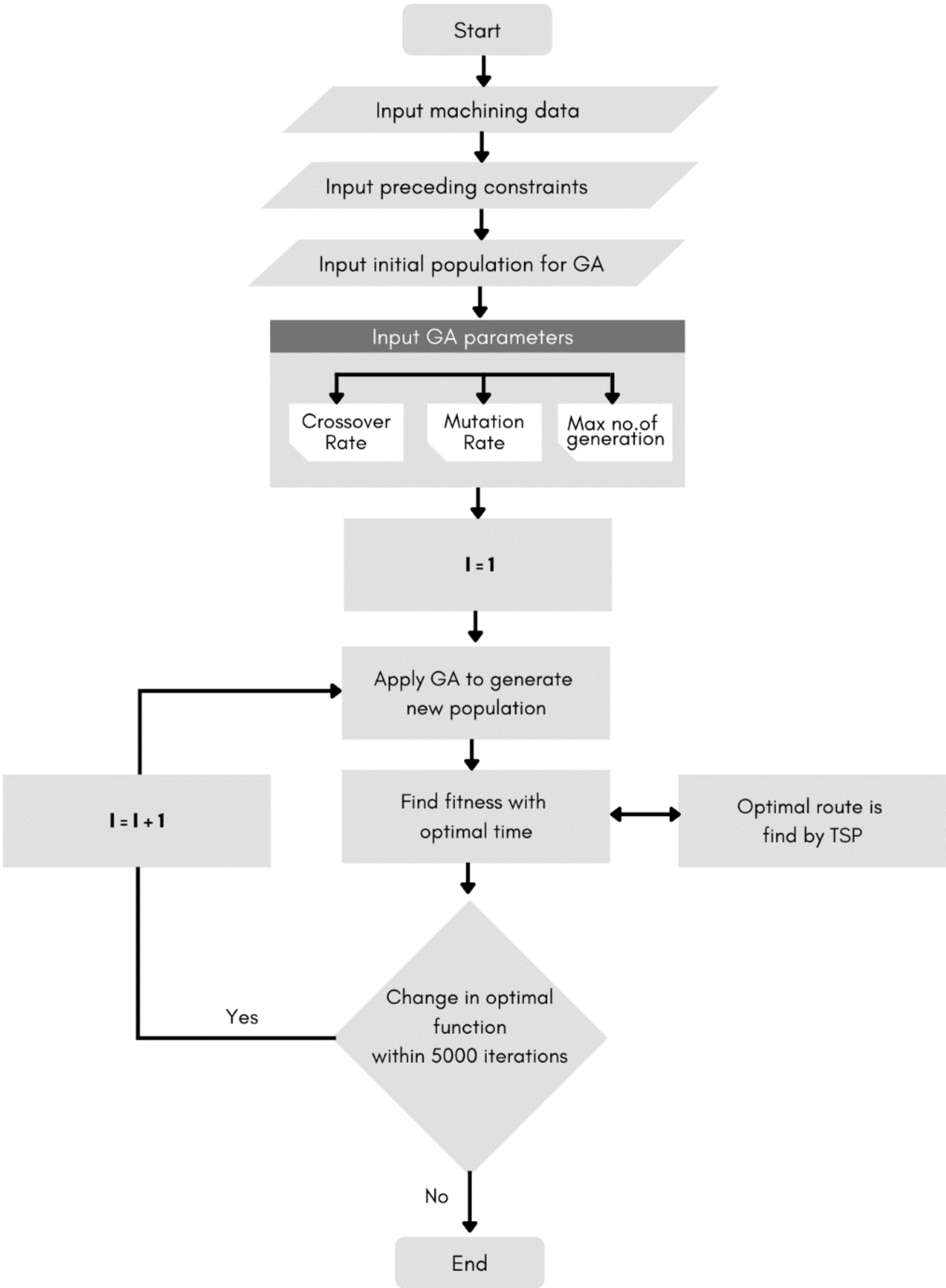

Figure 6: Proposed hybrid GA-TSP algorithm

3.4 Mathematical Model of Modified mTSP

The following mathematical models are used to find the optimal toolpath distance and time.

3.4.1 Notation

The proposed mathematical model employs the following notations.

O_i	:	Operation i in the sequence
D_{total}	:	Total Distance
TT_{total}	:	Total Travel Time
n	:	Number of operations
Sd	:	Safe distance
Rs	:	Rapid Speed of the cutting tool
ST	:	Tool switching time
nt	:	Number of tool switches
St	:	Time required to move from current point to switch point.
M_1	:	Machine 1
M_2	:	Machine 2
M_i	:	Next Machine
M_m	:	m^{th} Machine

3.4.1.1 Airtime

Airtime is defined as the cutting tool's time that moves from one point to another. A major part of the non-productive time during multiple machining operations is accounted to airtime.

3.4.1.2 Safe Distance

The tool will move from the endpoint to the tool switching point at a safe distance in the case of the next operation, which may use a different cutting tool. The cutting tool moves the safe distance upward and downward to avoid colliding with the workpiece.

3.4.1.3 Tool Switching Point

The point or location where the machine's cutting tool is changed is defined as the tool switching point. This is the location where all the cutting tools are arranged. As a result, the machine will select the appropriate cutting tool for each operation.

3.4.1.4 Rapid Speed

The cutting tool can move from one point to another at a certain speed. This speed can have a direct impact on the amount of non-productive time. This speed is termed the rapid speed.

3.4.1.5 Tool Switching Time

If the current and next operation requires a different cutting tool, the tool head should be replaced with the corresponding cutting to carry the next operation. For that, the cutting tool head will move to the tool switching point and change the tool. This amount of time required to switch between tools is defined as the tool switching time. The time taken to switch tools is determined by two factors. The first is the time it takes to change the cutting tool bit (Ct), and the second is the location from which the cutting tool moves to the tool changing point and where the next operation will begin.

For all cases of the production conditions, the airtime and non-productive time can be calculated as shown below.

3.4.2 Single Machine Production Line System (SMPLS)

Here, a series production with only one machine is considered in this section. This single machine can perform various machining operations. Each workpiece has a certain set of features. Some operations may be located on one plane, whereas others are in a second plane.

3.4.2.1 Case 1: for Single Plane

Case 1 discusses the different machining conditions on the single plane workpiece.

Given operations (O_1, O_2, O_3, ..., O_i, O_n), need to be machined in the production line of a single machine tool.

Find the D_{total}, so that the TT_{total} is minimized.

Here, O_i denotes the operation *i* in the sequence, and *n* denotes the number of operations.

The total distance and travel time can be calculated for various cases as follows:

$$D_{total} = \sum_{i=1}^{n-1} Dij, j = j + 1 \quad (1)$$

The distance Dij in Equation 1 between O_i and O_j, j = i+1 can be calculated as follows:

a. If the current operation and the next operation use the same cutting tool, then the distance *Dij*, between the two nodes can be calculated using Equation 2 and shown in Figure 7.

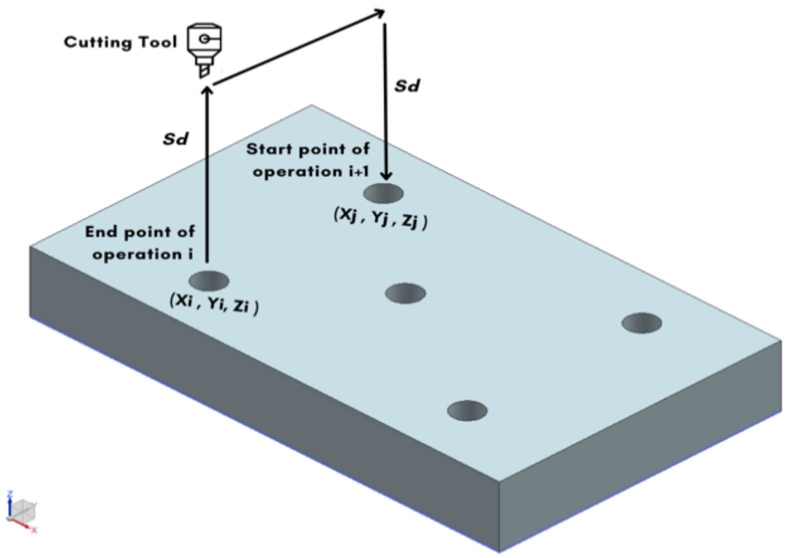

Figure 7: Same cutting tool for two adjacent nodes

$$Dij = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2} + 2 * Sd \quad (2)$$

Considering the rapid speed of Rs and based on Equation 1, the total time can be calculated by using Equation 3.

$$TT_{total} = \frac{(\sum_{i=1}^{n-1} Dij)}{Rs} \quad (3)$$

or

$$\text{TT}_{\text{total}} = \frac{\sum_{i=1}^{n-1}\left(\sqrt{\left(x_j - x_i\right)^2 + \left(y_j - y_i\right)^2} + 2 * Sd\right)}{Rs} \quad (4)$$

Where *Sd* is a predefined safe distance and *Rs* is the predefined travel (rapid) speed.

b. If the current operation and the next operation use different cutting tools, then the distance *Dij* between the two nodes can be calculated using Equation 5 and shown in Figure 8.

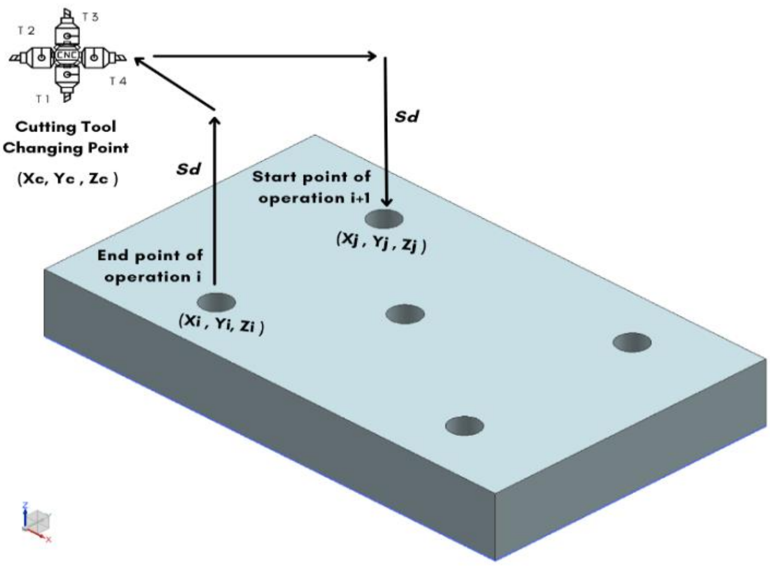

Figure 8: The different cutting tools used between two adjacent nodes

Note: For hole operations, the locations x_i, y_i, z_i, x_{is}, y_{is}, z_{is} and x_{ie}, y_{ie}, z_{ie} are the same.

$$Dij = \sqrt{(x_c - x_{ie})^2 + (y_c - y_{ie})^2 + (z_c - z_{ie})^2} + \sqrt{\left(x_{js} - x_c\right)^2 + \left(y_{js} - y_c\right)^2 + \left(z_{js} - z_c\right)^2} + 2 * Sd \quad (5)$$

Where,

(X_c, Y_c, Z_c) is the cutting tool change location.

(X_{js}, Y_{js}, Z_{js}) is the start point of the next operation.

(X_{ie}, Y_{ie}, Z_{ie}) is the endpoint of the current operation

Substitute Eq. 5 to find $TT_{total.}$

$$TT_{total} = \sum_{i=1}^{n-1} Dij \Big/ Rs + \sum_{i=1}^{nt-1} ST \qquad (6)$$

Where *nt* is the total number of times the tool is switched during the whole process.

3.4.2.2 Case 2: For Multi Planes

Case 2 discusses the different machining conditions on multiple planes of the workpiece.

a. If the current operation and the subsequent operation use the same cutting tool, then the distance Dij, between the two nodes can be calculated using Equation 7 and shown in Figure 9.

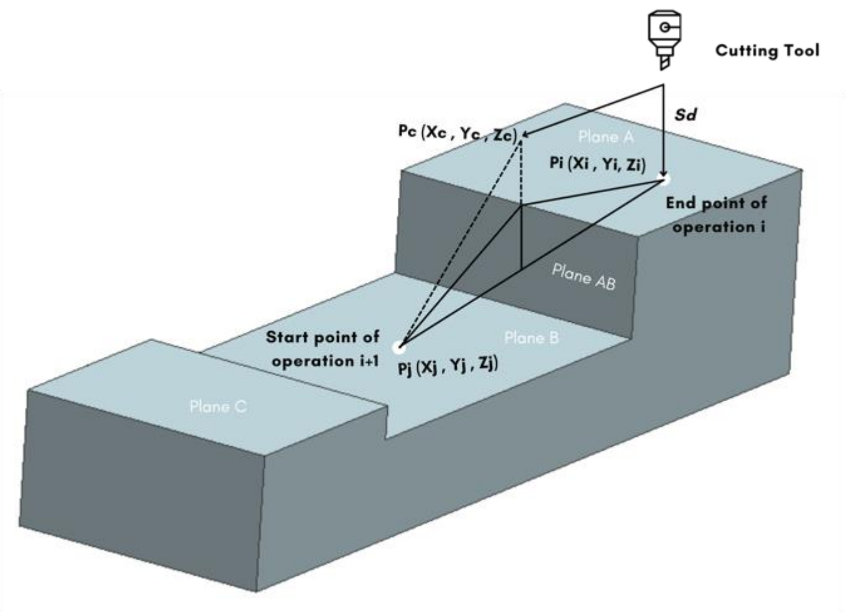

Figure 9: The different cutting tools used between two adjacent nodes

Consider the points $P(x_i, y_i, z_i)$ and $P(x_j, y_j, z_j)$ in Figure 9 located in planes A and B, respectively. The toolpath should pass through an imaginary point to move the tool safely between the points Pi and Pj (point P_c in Figure 9). Thus, the distance D_{ij} between points Pi and Pj can be calculated using Equation 7.

$$Dij = \sqrt{(x_j - x_c)^2 + (y_j - y_c)^2 + (zj - zc)^2} + \sqrt{(x_c - x_i)^2 + (y_c - y_i)^2 + (zc - zi)^2} + 2 * Sd \quad (7)$$

$$TT_{total} = \sum_{i=1}^{n-1} Dij \Big/ Rs \quad (8)$$

or

$$TT_{total} = \frac{\sqrt{(x_j - x_c)^2 + (y_j - y_c)^2 + (zj - zc)^2} + \sqrt{(x_c - x_i)^2 + (y_c - y_i)^2 + (zc - zi)^2} + 2 * Sd}{Rs} \quad (9)$$

The location of the imaginary point P_c can be determined using the following steps.

Step 1: Read the coordinates of three points in plane AB, such as

P_1 (x_1, y_1, z_1), P_2 (x_2, y_2, z_2) and P_3 (x_3, y_3, z_3)

Step 2: Find the equation of plane AB.

The plane passing through three points P_1, P_2, and P_3 can be determined by carrying out the following rule.

Step 2.1: Use the three points P_1, P_2, and P_3 to find vectors $\overrightarrow{P_2}$ and $\overrightarrow{P_1P_3}$ by using Equation (10) and (11) respectively.

$$\overrightarrow{P_1P_2} = \langle x_2 - x_1, y_2 - y_1, z_2 - z_1 \rangle \quad (10)$$

$$\overrightarrow{P_1P_3} = \langle x_3 - x_1, y_3 - y_1, z_3 - z_1 \rangle \quad (11)$$

Step 2.2: Find a normal vector n to the plane AB.

The normal vector, $\vec{n}$, to the plane is the cross product of vectors $\overrightarrow{P_1P_2}$ and $\overrightarrow{P_1P_3}$. The normal vector can be determined by using Equation 12.

$$\vec{n} = \overrightarrow{P_1P_2} \times \overrightarrow{P_1P_3} = \begin{bmatrix} (y_2 - y_1) & (z_2 - z_1) \\ (y_3 - y_1) & (z_3 - z_1) \end{bmatrix} \vec{\imath} - \begin{bmatrix} (x_2 - x_1) & (z_2 - z_1) \\ (x_3 - x_1) & (z_3 - z_1) \end{bmatrix} \vec{\jmath} + \begin{bmatrix} (x_2 - x_1) & (y_2 - y_1) \\ (x_3 - x_1) & (y_3 - y_1) \end{bmatrix} \vec{k} \quad (12)$$

Where;

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} = ad - bc$$

Step 2.3: Use P_1 and $\vec{n}$ to find the equation of the plane AB as follows.

$$A(x - x_1) + B(y - y_1) + C(z - z_1) = 0 \quad (13)$$

Where;

$$A = (y_2 - y_1)(z_3 - z_1) - (z_2 - z_1)(y_2 - y_1)$$

$$B = (x_2 - x_1)(z_3 - z_1) - (z_2 - z_1)(x_3 - x_1) \text{ and}$$

$$C = (x_2 - x_1)(y_3 - y_1)(y_2 - y_1)(x_3 - x_1)$$

Step 3: Find the equation of the line $\overrightarrow{P_iP_j}$ that passes through the points P_i and P_j. The line passing through the two points P_i and P_j can be determined by carrying out the following rule.

Step 3.1: Find a vector parallel to the line by using the vector between the two points as given in Equation 14.

$$\overrightarrow{P_iP_j} = (x_j - x_i)\vec{\imath} - (y_j - y_i)\vec{\jmath} + (z_j - z_i)\vec{k} \quad (14)$$

Step 3.2: Use the components of $\overrightarrow{P_iP_j}$ and P_i to express the parametric equation of the line by using Equation (15).

$$x = x_i + (x_j - x_i)t;$$

$$y = y_i + (y_j - y_i)t; \qquad (15)$$

$$x = z_i + (z_j - z_i)t;$$

Step 3.3: Solve t in each of x, y, and z in Equation (15) to find the symmetric as given in Equation (16).

$$\frac{(x-x_i)}{(x_j-x_i)} = \frac{(y-y_i)}{(y_j-y_i)} = \frac{(z-z_i)}{(z_j-z_i)} \qquad (16)$$

Step 4: Find the intersection point P_{int} (x_{int}, y_{int}, z_{int}) between the plane AB and the line $\overrightarrow{P_iP_j}$ by carrying out the following rule.

Step 4.1: Substitute the intersection point P_{int} (x_{int}, y_{int}, z_{int}) into the equation of the plane AB [Equation 13] as given in Equation 17.

$$A(x_{int} - x_1) + B(y_{int} - y_1) + C(z_{int} - z_1) = 0 \qquad (17)$$

Step 4.2: Substitute the intersection point P_{int} (x_{int}, y_{int}, z_{int}) into the equation of the line $\overrightarrow{P_iP_j}$ [Equation 15] as given in Equation 18.

$$x_{int} = x_i + (x_j - x_i)t_{int};$$

$$y_{int} = y_i + (y_j - y_i)t_{int}; \qquad (18)$$

$$z_{int} = z_i + (z_j - z_i)t_{int};$$

Step 4.3: Combine Equations 17 and 18 to find t_{int} .

Step 4.4: Substitute t_{int} into Equation 18 to find x_{int}, y_{int} and z_{int}.

Step 5: Find x, y and z coordinates of point P_c as follows.

$$x_c = x_{int},$$

$$y_c = y_{int} \tag{19}$$

$$z_c = z_i$$

b. If the current operation and the subsequent operation use different cutting tools, then the distance, Dij, between the two nodes can be calculated using Equation 20.

$$Dij = \sqrt{(x_c - x_i)^2 + (y_c - y_i)^2 + (z_c - z_i)^2} + \sqrt{(x_s - x_c)^2 + (y_s - y_c)^2 + (z_s - y_c)^2} + 2 \times Sd + (z_i - z_s) \tag{20}$$

Where;

(Xc, *Yc*, *X*z*)* is the cutting tool change location.

(Xi, Yi, Zi) is the endpoint of the current operation.

(Xs, Ys, Zs) is the start point of the next operation.

$$TT_{total} = \sum_{i=1}^{n-1} Dij / Rs + \sum_{i=1}^{nt-1} ST \tag{21}$$

Where *nt* is the total number of times that the tool is switched during the whole process and ST is the tool switching time.

3.4.3 Multi Machine Production Line System (MMPLS)

In this section, a series production with n number of machines is arranged in a series layout. Each machine can perform various machining operations. The workpiece will move from one machine to another through an automated transfer line system. The final product can be delivered through the nth machine. A sample illustration to demonstrate a production line flow is shown in Figure 10.

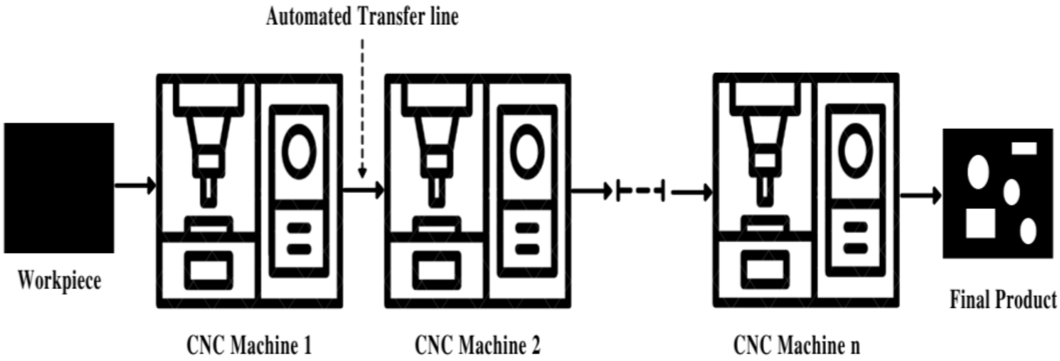

Figure 10: Production line with n number of machine units

Consider a production line with n machine units, M_1, M_2, … M_i, M_m

Given operations (O_1, O_2, O_3, …, O_i, O_n), need to be machined in a production line of multi-machine tools, where;

Operations (O_{i1}, O_{i2}, O_{i3}, …, O_{ij}, O_{mi}) are machined in M_i $\forall i=1, 2, 3, \ldots, m$, and n= m1+m2+m3
find the D_{total}
So that the TT_{total} is minimized.

The total travel time for the production line can be calculated as follows:

$$TT_{total} = \sum_{i=1}^{n} TM_i + (n-1) * Tr. \qquad (22)$$

Where;

n is the number of machine units in the production line.

TM_i is the travel time for machine i. TM_i can be calculated using the procedure mentioned in the previous section and *Tr* is the transfer time between machine *i*, and machine *i+1*, where *i = 1, 2, 3, …, n-1*

3.5 Developed Simulator Software

A computer program was developed to test the efficiency and benefits of the proposed technique. The previously defined mathematical model with GA and modified mTSP was coded during the software development phase to find the best sequence of operations for optimal production time. The entire computational software was written in C++ and ran on an Intel® core i7, 2.0 GHz processor. The Graphical User interface (GUI) and the simulation windows of the developed program user interface are shown in Figure 11 and Figure 12 respectively.

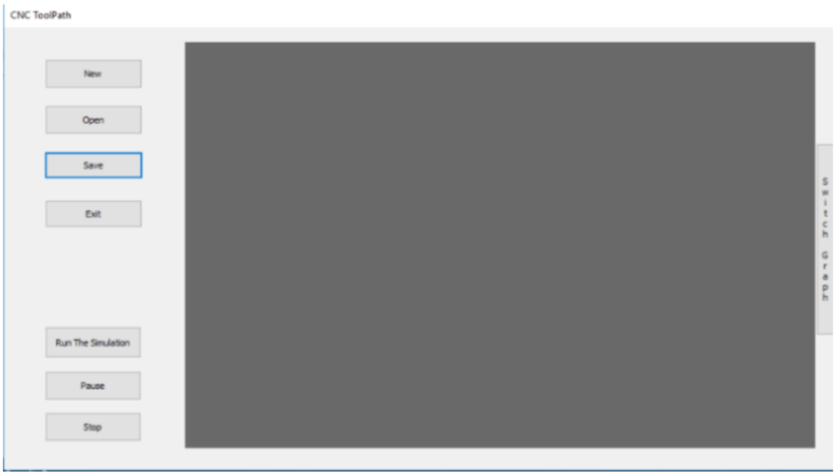

Figure 11: The main window of the developed software's GUI

In the main window of the GUI, we need to enter the input parameters for the current machining operation.

- Click on the new button to start a new machining operation.
- We need to upload the operation sheet for the current machining process in the open tab.
- After that, we need to start the simulation by clicking on the "Run the simulation" button.

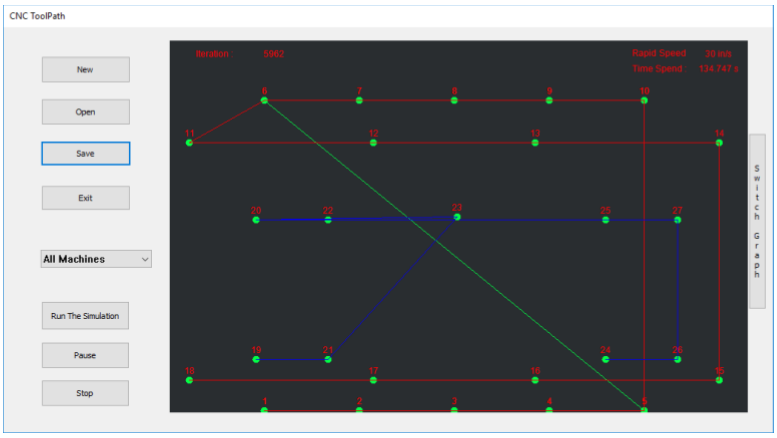

Figure 12: Simulation window for a random iteration based on the input file

The simulation will work to find the optimal sequence by using the mathematical model we developed. Each iteration will produce possible toolpath sequences in each machine. After possible iterations, the optimal sequence will be generated. If there is no change in sequences during consecutive 5000 iterations, the program will stop the simulation and generate the optimal toolpath sequence. Further simulations are discussed in the following chapters.

Chapter 4: Numerical Samples

The developed optimizer software is analyzed for its efficacy by testing various real-life manufacturing conditions. To check that, various workpiece illustrations with many holes and slots are created using NX modelling software, and its operation sheet is created to upload into the software. The various production conditions are discussed below.

4.1 PL 1: SMPLS

4.1.1 Case 1- Single Machine- Multi Cutting Tools – Single Plane

Case 1 is about machining various operations, including drilling and pocket milling carried on a single machine. Here the selected rectangular workpiece has 8 holes and 14 pockets to be machined, where all the operations are in the same plane itself. Since there are two kinds of machining operations, we need a cutting tool for drilling holes and another for making pocket milling. The isometric view and top view for the workpiece are shown in Figure 13 and Figure 14.

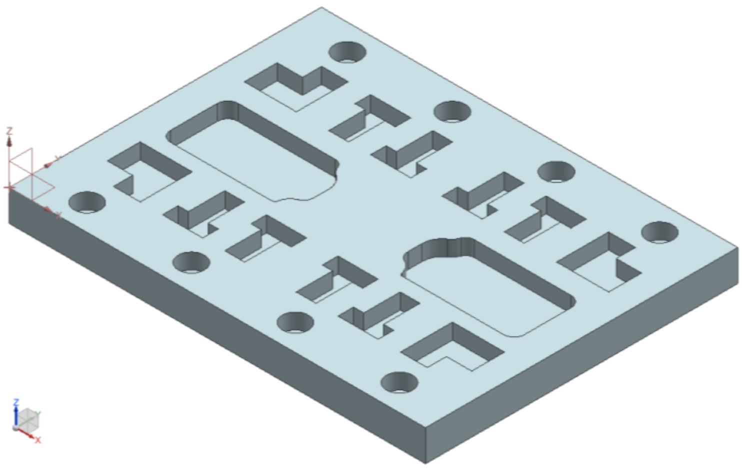

Figure 13: Isometric view generated on NX modeling software for case 1

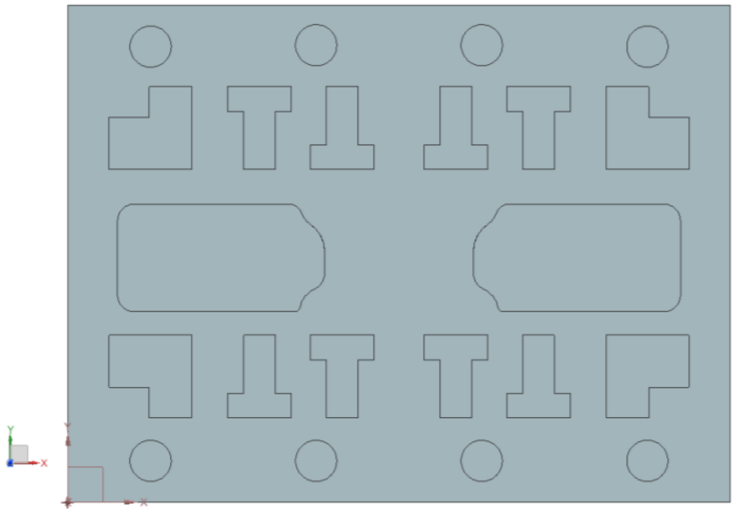

Figure 14: Top view of the workpiece generated for case 1

4.1.1.1 Operation sheet

For case 1, multiple operations including hole drilling and pocket milling should be performed. Here, all the holes are drilled by using tool number 1 and pocket milling is done by tool number 2. This is denoted as M:1 and M1:2, respectively. This operation sheet should be entered by the operator. The detailed operation sheet for case 1 is given in Table 1 as follows:

Table 1: Operation sheet for the case 1 workpiece

Process No.	**Process**	**Start Point (x, y, z)**	**End Point (x, y, z)**	**Capable Machines**	**Cutting Tool**
1	Drilling	50,25,0	50,25,0	M1	M1:1
2	Drilling	150,25, 0	100,25, 0	M1	M1:1
3	Drilling	250,25, 0	150,25, 0	M1	M1:1
4	Drilling	350,25, 0	200,25, 0	M1	M1:1
5	Drilling	50,275,0	50,275,0	M1	M1:1
6	Drilling	150,275.82,0	150,275.82,0	M1	M1:1
7	Drilling	250,275.82,0	250,275.82,0	M1	M1:1
8	Drilling	350,275,0	350,275,0	M1	M1:1
9	Milling	135,50.89,0	106.22,100.89,0	M1	M1:2
10	Milling	75,100.89,0	49.25,50.89,0	M1	M1:2

Table 1: Operation sheet for the case 1 workpiece (continued)

Process No.	Process	Start Point (x, y, z)	End Point (x, y, z)	Capable Machines	Cutting Tool
11	Milling	40,125,0	133.43,172,0	M1	M1:2
12	Milling	266.56,172,0	360,125,0	M1	M1:2
13	Milling	375,200.89,0	325,250.89,0	M1	M1:2
14	Milling	303.59,250.89,0	274.81,200.89,0	M1	M1:2
15	Milling	253.59,200.89,0	224.81,250.89,0	M1	M1:2
16	Milling	175.18,250.89,0	146.40,200.89,0	M1	M1:2
17	Milling	125.18,200.89,0	96.40,250.89,0	M1	M1:2
18	Milling	75,250.89,0	25,200.89,0	M1	M1:2
19	Milling	350.74,50.89, 0	325,100.89, 0	M2	M1:2
20	Milling	293.77,100.89,0	265,50.89, 0	M3	M1:2
21	Milling	243.77, 50.89, 0	215, 100.89, 0	M4	M1:2
22	Milling	185,100.89,0	156.22,50.8,0	M5	M1:2

4.1.2 Case 2 - Single Machine - Multi Cutting Tools - Multi Plane

Case 2 is about machining various operations, including drilling and pocket milling carried on a single machine. Here the selected rectangular workpiece has 26 holes and 14 pockets to be machined, where some of the operations are in the same plane itself. Since there are two kinds of machining operations, we need a cutting tool for drilling holes and another for making pocket milling. The isometric view and top view for the workpiece are shown in Figure 15 and Figure 16.

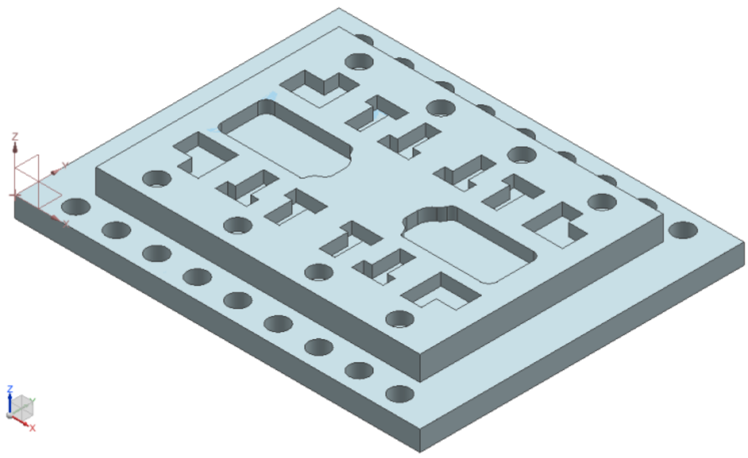

Figure 15: Isometric view generated on NX modeling software for case 2

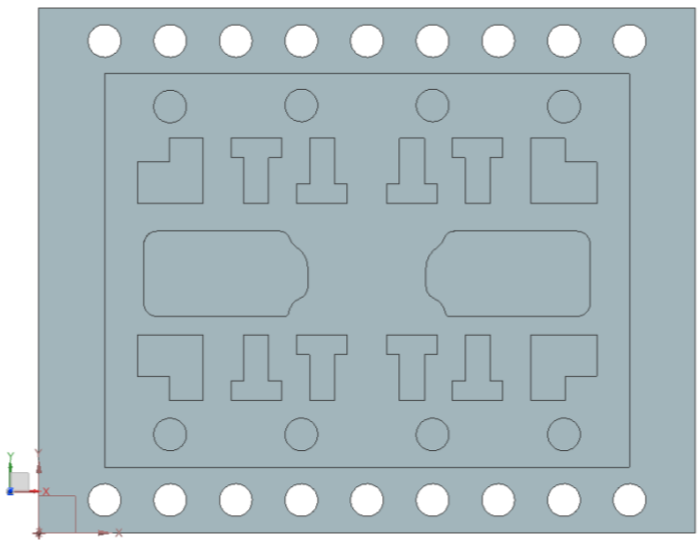

Figure 16: Top view of the workpiece generated for case 2

4.1.2.1 Operation Sheet

For case 2, multiple operations including hole drilling and pocket milling should be performed. Here, all the holes are drilled by using tool number 1 and pocket milling is done by tool number 2. This is denoted as M:1 and M1:2, respectively. Here, some of the operations are done on one plane while the rest of them are on plane 2. The detailed operation sheet for case 2 is shown in Table 2.

Table 2: Operation sheet for the case 2 workpiece

Process No.	**Process**	**Start Point (x, y, z)**	**End Point (x, y, z)**	**Capable Machines**	**Cutting Tool**
1	Drilling	50,25,0	50,25,0	M1	M1:1
2	Drilling	100,25, 0	100,25, 0	M1	M1:1
3	Drilling	150,25, 0	150,25, 0	M1	M1:1
4	Drilling	200,25, 0	200,25, 0	M1	M1:1
5	Drilling	250,25, 0	250,25, 0	M1	M1:1
6	Drilling	300,25, 0	300,25, 0	M1	M1:1
7	Drilling	350, 25, 0	350, 25, 0	M1	M1:1
8	Drilling	400,25,0	400,25,0	M1	M1:1
9	Drilling	450,25,0	450,25,0	M1	M1:1
10	Drilling	450,375,0	450,375,0	M1	M1:1
11	Drilling	400,375,0	400,375,0	M1	M1:1
12	Drilling	350,375,0	350,375,0	M1	M1:1
13	Drilling	300,375,0	300,375,0	M1	M1:1
14	Drilling	250,375,0	250,375,0	M1	M1:1
15	Drilling	200,375,0	200,375,0	M1	M1:1
16	Drilling	150,375,0	150,375,0	M1	M1:1
17	Drilling	100,375,0	100,375,0	M1	M1:1
18	Drilling	50,375,0	50,375,0	M1	M1:1
19	Drilling	400,75,30	400,75,30	M1	M1:1
20	Drilling	300,75,30	300,75,30	M1	M1:1
21	Drilling	200,75,30	200,75,30	M1	M1:1
22	Drilling	100,75,30	100,75,30	M1	M1:1
23	Drilling	100,325,30	100,325,30	M1	M1:1
24	Drilling	200,325,30	200,325,30	M1	M1:1
25	Drilling	300,325,30	300,325,30	M1	M1:1
26	Drilling	400,325,30	400,325,30	M1	M1:1
27	Milling	375,100,30	425,151,30	M1	M1:2
28	Milling	353.59,100.89,30	324.81,150.89,30	M1	M1:2

Table 2: Operation sheet for the case 2 workpiece (continued)

Process No.	Process	Start Point (x, y, z)	End Point (x, y, z)	Capable Machines	Cutting Tool
29	Milling	303.59,150.89,30	274.81,100.89,30	M1	M1:2
30	Milling	235,150.89,30	206.22,100.89,30	M1	M1:2
31	Milling	175.18,150.89,30	146.40,100.89,30	M1	M1:2
32	Milling	125,150.89,30	99.25,100.89,30	M1	M1:2
33	Milling	425,250.89,30	375,300.89,30	M1	M1:2
34	Milling	353.59,300.89,30	324.81,250.89,30	M1	M1:2
35	Milling	293.77,300.89,30	265,250.89,30	M1	M1:2
36	Milling	235,250.89,30	206.22,300.89,30	M1	M1:2
37	Milling	185,300.89,30	156.22,250.89,30	M1	M1:2
38	Milling	125,300.89,30	75,250.89,30	M1	M1:2
39	Milling	90,220,30	195,187.91,30	M1	M1:2
40	Milling	316.56,222,30	410,175,30	M1	M1:2

4.2 PL 2: Infinite Machine Production Line System (IMPLS)

4.2.1 Case 3 - Two Machines - Multi Cutting Tool - Single Plane

Case 3 is about machining various operations, including drilling and pocket milling carried on a single machine. An irregular workpiece has 17 holes with five different diameters. Each hole needs a different set of processes to be completed. The isometric view and top view for the workpiece are shown in Figure 17 and Figure 18.

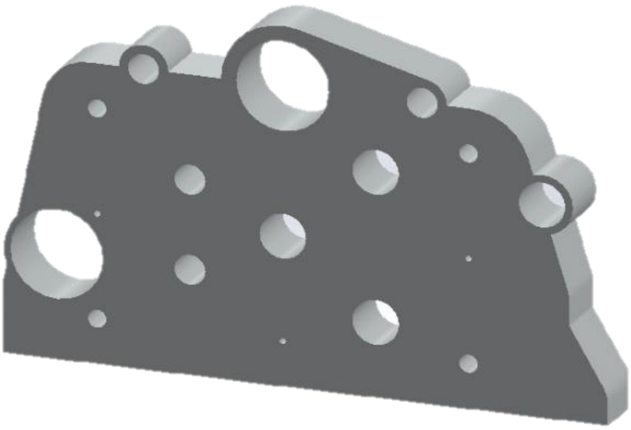

Figure 17: Isometric view generated for 2M production line case

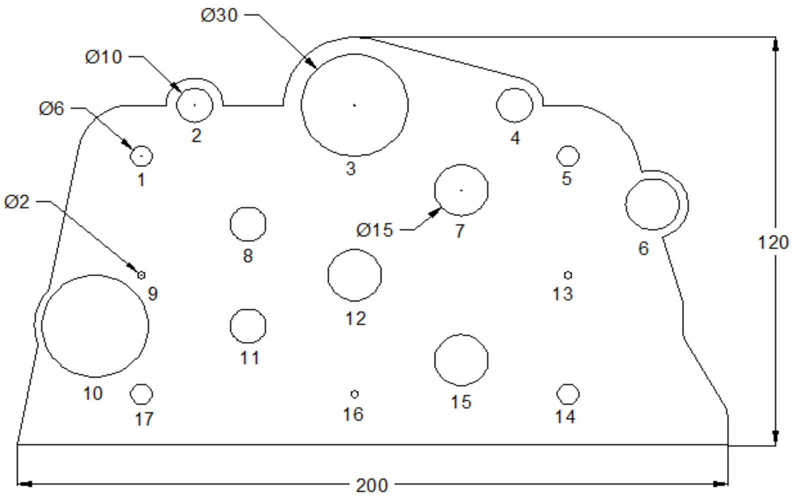

Figure 18: Top view generated for 2M production line case

4.2.1.1 Operation Sheet

For case 3, multiple hole drilling operations with different diameters should be performed. Here, each set of holes is drilled by using certain cutting tools and multiple machines. The detailed operation sheet for case 3 is shown in Table 3.

Table 3: Operation sheet for the case 3 workpiece

Process No.	**Process**	**Start Point (x, y, z)**	**End point (x, y, z)**	**Possible Machine**	**Cutting Tool**
1A	Center drill	(35, 85,0)	(35, 85, 0)	M1, M2	M1:1;M2:2
1B	Drilling	(35, 85,0)	(35, 85, 0)	M1, M2	M1:2;M2:4
1C	Tapping	(35, 85, 0)	(35, 85, 0)	M1	M1:7
2A	Center drill	(50,100, 0)	(50, 100, 0)	M1, M2	M1:1;M2:2
2B	Drilling	(50,100,0)	(50, 100, 0)	M1, M2	M1:3;M2:5
3A	Center drill	(95,100,0)	(95, 100, 0)	M1, M2	M1:1; M2:2
3B	Drilling	(95,100,0)	(95,100, 0)	M1	M1:5
3C	Drilling	(95, 100, 0)	(95,100, 0)	M2	M2:3
4A	Center drill	(140,100,0)	(140,100,0)	M1, M2	M1:1;M2:2
4B	Drilling	(140,100,0)	(140,100,0)	M1, M2	M1:3;M2:5
5A	Center drill	(155, 85, 0)	(155, 85, 0)	M1, M2	M1:1;M2:2
5B	Drilling	(155, 85, 0)	(155, 85, 0)	M1, M2	M1:2;M2:4
5C	Tapping	(155, 85, 0)	(155, 85, 0)	M1	M1:7
6A	Center drill	(180, 70, 0)	(180, 70, 0)	M1, M2	M1:1;M2:2
6B	Drilling	(180, 70, 0)	(180, 70, 0)	M1, M2	M1:4;M2:6
6C	Reaming	(180, 70, 0)	(180, 70, 0)	M2	M2:7
7A	Center drill	(125, 75, 0)	(125, 75, 0)	M1, M2	M1:1;M2:2
7B	Drilling	(125, 75, 0)	(125, 75,0)	M1, M2	M1:4;M2:6
7C	Reaming	(125, 75, 0)	(125, 75,0)	M2	M2:7
8A	Center drill	(65, 65, 0)	(65, 65, 0)	M1, M2	M1:1;M2:2
8B	Drilling	(65, 65, 0)	(65, 65, 0)	M1, M2	M1:3;M2:5
9A	Center drill	(35, 50, 0)	(35, 50, 0)	M1, M2	M1:1;M2:2
9B	Drilling	(35, 50, 0)	(35, 50, 0)	M1, M2	M1:6;M2:1
9C	Reaming	(35, 50, 0)	(35, 50, 0)	M2	M2:8
10A	Center drill	(22, 35, 0)	(22, 35, 0)	M1, M2	M1:1;M2:2
10B	Drilling	(22, 35, 0)	(22, 35, 0)	M1	M1:5

Table 3: Operation sheet for the case 3 workpiece (continued)

Process No.	**Process**	**Start Point (x, y, z)**	**End Point (x, y, z)**	**Possible Machine**	**Cutting Tool**
10C	Drilling	(22, 35, 0)	(22, 35, 0)	M2	M2:3
11A	Center drill	(65, 35, 0)	(65, 35, 0)	M1, M2	M1:1;M2:2
11B	Drilling	(65, 35, 0)	(65, 35, 0)	M1, M2	M1:3;M2:5
12A	Center drill	(95, 50, 0)	(95, 50, 0)	M1, M2	M1:1;M2:2
12B	Drilling	(95, 50, 0)	(95, 50, 0)	M1, M2	M1:4;M2:6
12C	Reaming	(95, 50, 0)	(95, 50, 0)	M2	M2:7
13A	Center drill	(155, 50, 0)	(155, 50, 0)	M1, M2	M1:1;M2:2
13B	Drilling	(155, 50, 0)	(155, 50, 0)	M1, M2	M1:6;M2:1
13C	Reaming	(155, 50, 0)	(155, 50, 0)	M2	M2:8
14A	Center drill	(155, 15, 0)	(155, 15, 0)	M1, M2	M1:1;M2:2
14B	Drilling	(155, 15, 0)	(155, 15, 0)	M1, M2	M1:2;M2:4
14C	Tapping	(155, 15, 0)	(155, 15, 0)	M1	M1:7
15A	Center drill	(125, 25 ,0)	(125, 25 ,0)	M1, M2	M1:1;M2:2
15B	Drilling	(125, 25 ,0)	(125, 25 ,0)	M1, M2	M1:4;M2:6
15C	Reaming	(125, 25 ,0)	(125, 25 ,0)	M2	M2:7
16A	Center drill	(95, 15, 0)	(95, 15, 0)	M1, M2	M1:1;M2:2
16B	Drilling	(95, 15, 0)	(95, 15, 0)	M1, M2	M1:6;M2:1
16C	Reaming	(95, 15, 0)	(95, 15, 0)	M2	M2:8
17A	Center drill	(35, 15, 0)	(35, 15, 0)	M1, M2	M1:1;M2:2
17B	Drilling	(35, 15, 0)	(35, 15, 0)	M1, M2	M1:2;M2:4
17C	Tapping	(35, 15, 0)	(35, 15, 0)	M1	M1:7

4.2.1.2 Constraints

Constraints are the restriction on each process to be performed. Here, four operations are to be done at certain points. There will be a set of operations that have preceding and succeeding processes for every case. The preceding operation should be done first and follow the successful operations. Hence the sequence of operations should be found based on these constraints. The operator should tabulate these constraints. The information about the constraints is shown in the following Table 4.

Table 4: Constraints for case 3 workpiece

Constraints No.	Preceding	Succeeding
1	1A	1B, 1C
2	2A	2B
3	3A	3B, 3C
4	6A	6B, 6C
5	9A	9B, 9C

4.2.2 Case 4 - Six Machines – Multi Cutting Tools - Multi Planes

This case is about to discuss the multiple operations in a 6M production line system. Here six machines are arranged in a series production line layout. Each machine can perform a certain set of operations. Machining operations like drilling with different diameters and pockets with different dimensions will be required here. So, selecting the cutting tools and machines is vital in optimal sequence selection.

A rectangular workpiece with 18 holes and 9 pockets is used for case 4. Here, some of the operations are in the same plane and the rest of them are in a different plane. Since many types of machining operations are required, we need different cutting tools for drilling holes with different diameters and different types of pockets. Also, 6 machines are arranged in a series layout to complete the entire machining process. The isometric view and top view for the workpiece are shown in Figure 19 and Figure 20.

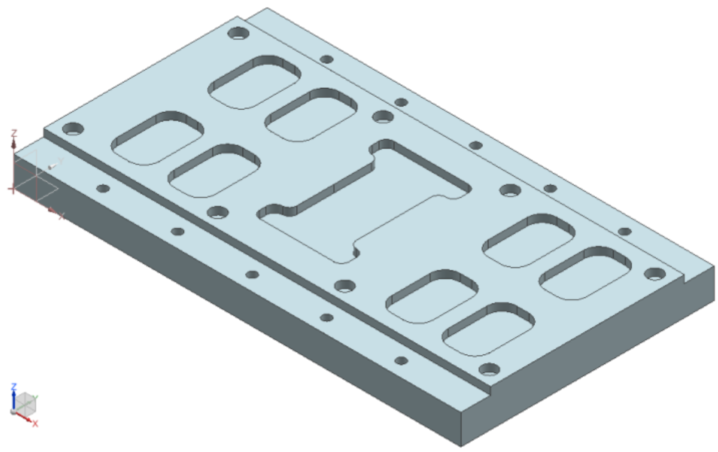

Figure 19: Isometric view generated on NX modeling software

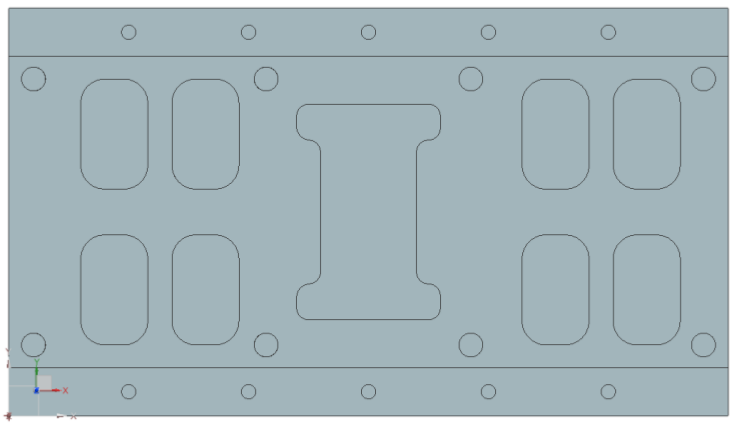

Figure 20: Top view generated on NX modeling software

4.2.2.1 Operation Sheet

For case 4, multiple operations including hole drilling and pocket milling should be performed. The detailed operation sheet for case 4 is shown in Table 5.

Table 5: Operation sheet for the case 4 workpiece

Process No.	**Process**	**Start Point (x, y, z)**	**End Point (x, y, z)**	**Capable Machines**	**Cutting Tool**
1A	Drilling	50,15,15	50,15,15	M1, M2, M3, M6	M1:1;M2:3; M3:7;M6:9
1B	Reaming	50,15,15	50,15,15	M2, M3	M2:7;M3:4
2A	Drilling	100,15,15	100,15,15	M1, M2, M3, M6	M1:1;M2:3; M3:7;M6:9
2B	Reaming	100,15,15	100,15,15	M2, M3	M2:7;M3:4
3A	Drilling	150,15,15	150,15,15	M1, M2, M3, M6	M1:1;M2:3; M3:7;M6:9
3B	Reaming	150,15,15	150,15,15	M2, M3	M2:7;M3:4
4A	Drilling	200,15,15	200,15,15	M1, M2, M3, M6	M1:1;M2:3; M3:7;M6:9
4B	Reaming	200,15,15	200,15,15	M2, M3	M2:7;M3:4
5A	Drilling	250,15,15	250,15,15	M1, M2, M3, M6	M1:1;M2:3; M3:7;M6:9
5B	Reaming	250,15,15	250,15,15	M2, M3	M2:7;M3:4
6A	Drilling	50,160,15	50,160,15	M1, M2, M3, M6	M1:1;M2:3; M3:7;M6:9
6B	Reaming	50,160,15	50,160,15	M2, M3	M2:7;M3:4
7A	Drilling	100,160,15	100,160,15	M1, M2, M3, M6	M1:1;M2:3; M3:7;M6:9
7B	Reaming	100,160,15	100,160,15	M2, M3	M2:7;M3:4
8A	Drilling	150,160,15	150,160,15	M1, M2, M3, M6	M1:1;M2:3; M3:7;M6:9
8B	Reaming	150,160,15	150,160,15	M2, M3	M2:7;M3:4
9A	Drilling	200,160,15	200,160,15	M1, M2, M3, M6	M1:1;M2:3; M3:7;M6:9
9B	Reaming	200,160,15	200,160,15	M2, M3	M2:7;M3:4
10A	Drilling	250,160,15	250,160,15	M1, M2, M3, M6	M1:1;M2:3; M3:7;M6:9

Table 5: Operation sheet for the case 4 workpiece (continued)

Process No.	Process	Start Point (x, y, z)	End Point (x, y, z)	Capable Machines	Cutting Tool
10B	Reaming	250,160,15	250,160,15	M2, M3	M2:7;M3:4
11	Drilling	10.32,140.5,19	10.32,140.5,19	M2, M3, M5	M2:9;M3:3; M5:4
12	Drilling	107.32,140.5,19	107.32,140.5,19	M2, M3, M5	M2:9;M3:3; M5:4
13	Drilling	192.67,140.5,19	192.67,140.5,19	M2, M3, M5	M2:9;M3:3; M5:4
14	Drilling	289.67,140.5,19	289.67,140.5,19	M2, M3, M5	M2:9;M3:3; M5:4
15	Drilling	289.67,29.5,19	289.67,29.5,19	M2, M3, M5	M2:9;M3:3; M5:4
16	Drilling	192.67,29.5,19	192.67,29.5,19	M2, M3, M5	M2:9;M3:3; M5:4
17	Drilling	107.32,29.5,19	107.32,29.5,19	M2, M3, M5	M2:9;M3:3; M5:4
18	Drilling	10.32,29.5,19	10.32,29.5,19	M2, M3, M5	M2:9;M3:3; M5:4
19	Pocket milling	45.57,39.14,19	35.28,65.17,15	M4,M6	M4:5;M6:1
20	Pocket milling	45.57,104.20,19	35.28,130.27,15	M4,M6	M4:5;M6:1
21	Pocket milling	83.57,39.14,19	73.28,65.17,15	M4,M6	M4:5;M6:1
22	Pocket milling	83.57,104.20,19	73.28,130.27,15	M4,M6	M4:5;M6:1
23	Pocket milling	151.57,105.52,19	125,48.06,15	M4,M6	M4:5;M6:1
24	Pocket milling	229.57,39.14,19	219.28,65.17,15	M4,M6	M4:5;M6:1
25	Pocket milling	229.57,104.20,19	219.29,130.27,15	M4,M6	M4:5;M6:1
26	Pocket milling	267.57,39.14,19	257.28,65.17,15	M4,M6	M4:5;M6:1

Table 5: Operation sheet for the case 4 workpiece (continued)

Process No.	**Process**	**Start Point (x, y, z)**	**End Point (x, y, z)**	**Capable Machines**	**Cutting Tool**
27	Pocket milling	267.57,104.20,19	257.28,130.27,15	M3,M4,M6	M3:7;M4:5; M6:1

4.2.2.2 Constraints

Constraints are the restriction on each process to be performed. Here, four operations are to be done at certain points. There will be a set of operations that have preceding and succeeding processes for every case. The preceding operation should be done first and follow the successful operations. Hence the sequence of operations should be found based on these constraints. The information about the constraints is shown in the following Table 6.

Table 6: Constraints for case 4 workpiece

Constraints No.	**Preceding**	**Succeeding**
1	1A	1B
2	2A	2B
3	3A	3B
4	4A	4B
5	5A	5B
6	6A	6B
7	7A	7B
8	8A	8B
9	9A	9B
10	10A	10B

Based on these operation sheets and constraints table, each workpiece models will be analyzed, and the optimal sequence will be find using the developed software. The result of each case is discussed in the next chapter.

Chapter 5: Results

Various CNC machining conditions discussed in the previous chapter have been simulated in the developed software. The simulation was done based on the operation sheet provided with each case. The developed software calculated the optimal non-productive toolpath in CNC machining systems by using the Hybrid GA- Multiple mTSp optimization techniques. The software-generated results are discussed in the following sections.

5.1 Simulation Results

5.1.1 Case 1 – Single Machine- Multi Cutting Tools – Single Plane

For case 1, initial machining parameters are given to the GUI of the developed simulator as follows and shown in Figure 21.

Rapid speed :30 mm/sec

Tool switching point: (0, 0, 100)

Safe distance: (0, 0, 50)

Cutting tool change time: 30 seconds

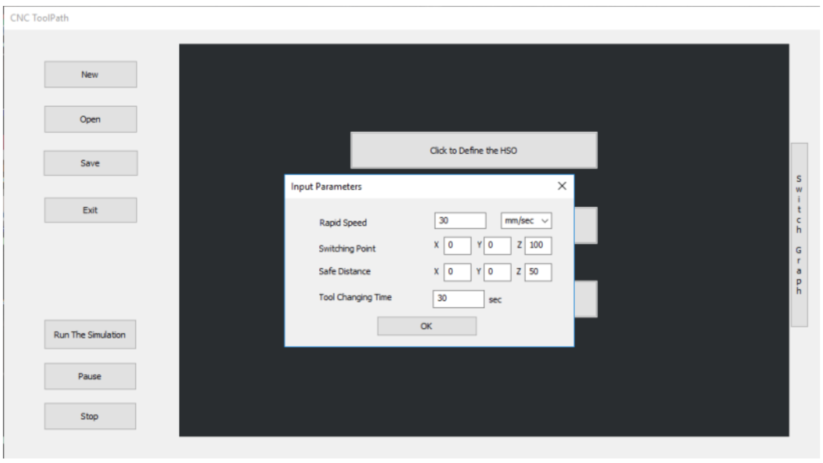

Figure 21: Input parameters in GUI for case 1

The simulator initiates the simulation with the machining data, operation sheet and constraints table. The program runs with a proposed mathematical model with the selected mutation rate, crossover rate and a maximum number of populations. The initial iteration for case 1 is shown in Figure 22.

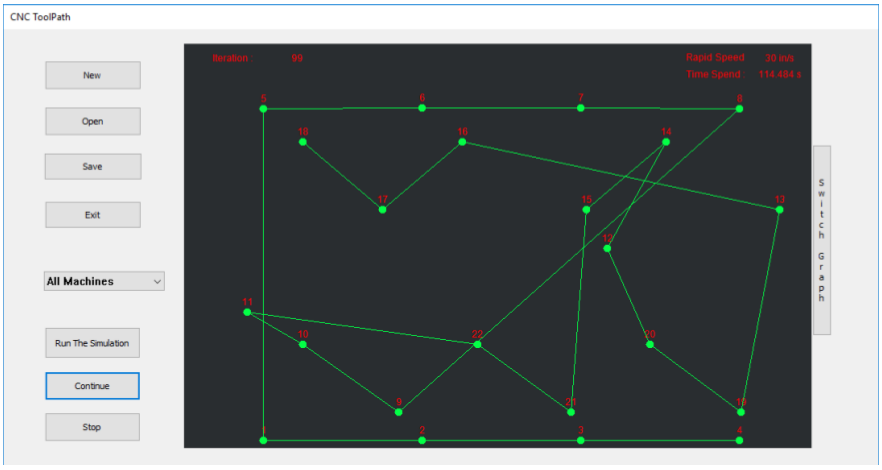

Figure 22: Toolpath sequence generated on the workpiece after 99 iterations

After 99 iterations, the total non-productive time calculated based on the generated sequence was 114.484 sec. At 507 th iteration, the toolpath sequence has been modified into the shortest path with a total time of 104.893 sec. This is shown in Figure 23.

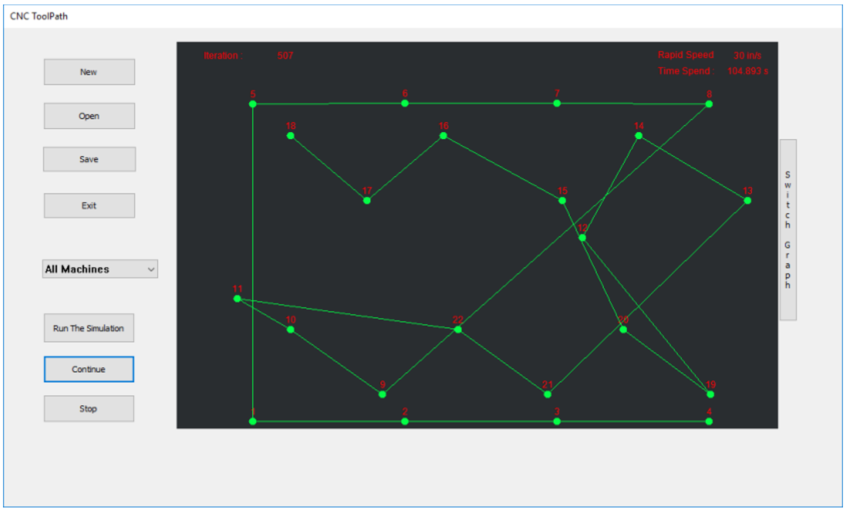

Figure 23: Toolpath sequence generated on the workpiece after 507 iterations

The optimal toolpath was found after 8454 iterations. The optimal time was 116.60 seconds, which gradually decreased to 104.893 seconds at the 507th iteration.

After 8454 iterations, the optimal toolpath sequence is obtained in 103.981 seconds. This is shown in Figure 24.

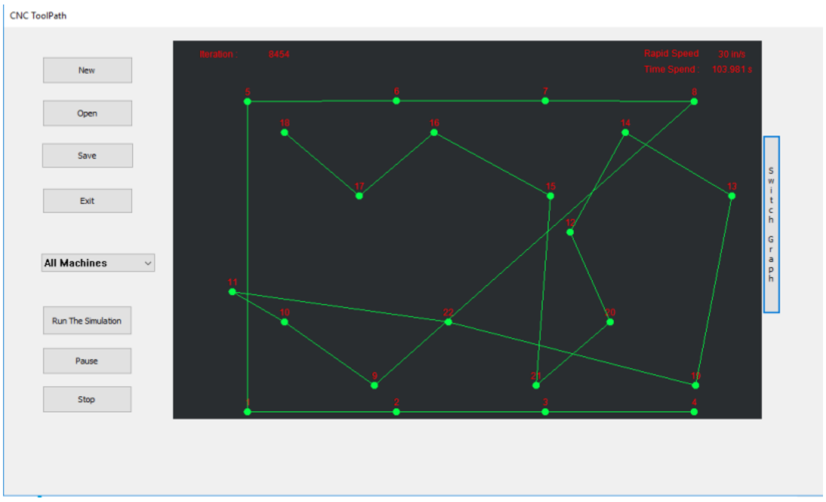

Figure 24: Optimal toolpath sequence generated after 8454 iterations

The optimal non-productive time, including airtime and tool switching time in a single machine unit, is calculated here. The optimal operational sequence generated by the proposed simulator is shown in Table 7.

Table 7: Optimal toolpath sequence for case 1 generated by the software

Operation	Machine	Tool	Optimal Time Spend
4	M1	1	103.981
3	M1	1	
2	M1	1	
1	M1	1	
5	M1	1	
6	M1	1	
7	M1	1	
8	M1	1	
9	M1	2	
10	M1	2	
11	M1	2	
22	M1	2	
19	M1	2	
13	M1	2	
14	M1	2	
12	M1	2	
20	M1	2	
21	M1	2	
15	M1	2	
16	M1	2	
17	M1	2	
18	M1	2	

The optimal toolpath sequence developed is obtained by minimizing the tool switching and airtime. The same workpiece is also simulated in Nx modelling and Simulating software. The results from Nx software are shown in Figure 25 and Figure 26.

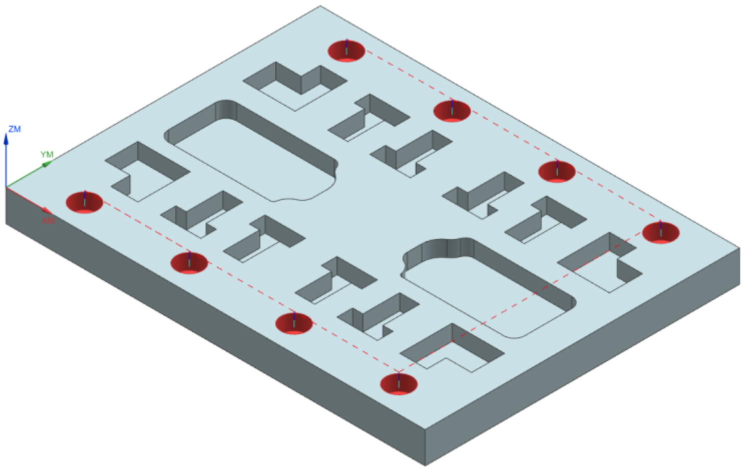

Figure 25: Shortest drilling toolpath generated for case 1

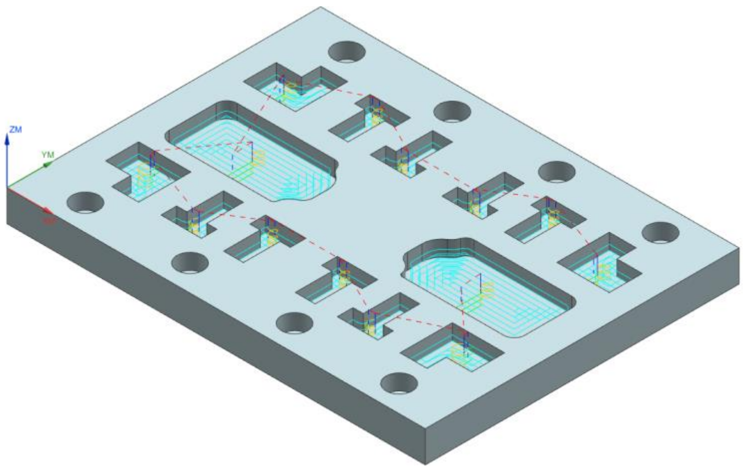

Figure 26: Shortest pocket cutting toolpath generated for case 1

Figure 25 and Figure 26 shows the shortest drilling path and pocket cutting path, respectively. For hole drilling operations, starting and endpoints for any operations will be the same, whereas the start and endpoints will be different in the pocket milling operation.

5.1.2 Case 2-Single Machine - Multi Cutting Tools - Multi Planes

For case 2, initial machining parameters are given to the GUI of the developed simulator as follows and shown in Figure 27.

Rapid speed :30 mm/sec

Tool switching point: (10, 10, 100)

Safe distance: (0, 0, 70)

Cutting tool change time: 40 seconds

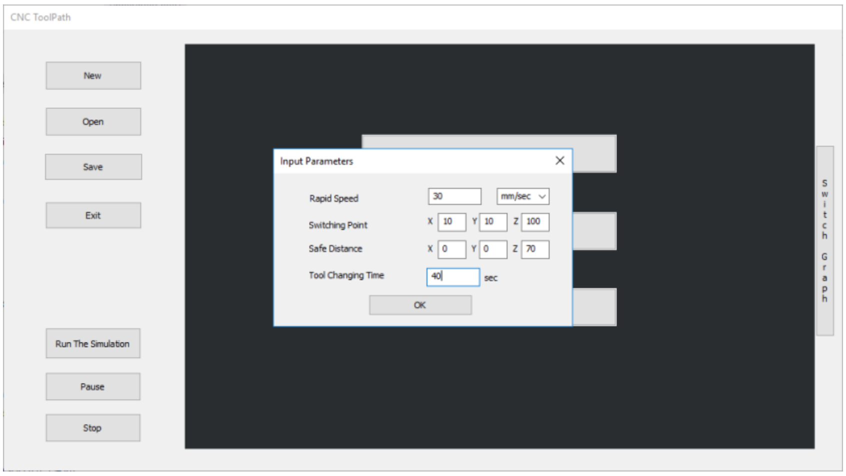

Figure 27: Input parameters in GUI for case 2

The simulator initiates the simulation with the machining data, operation sheet, and constraints table. The program runs with the proposed mathematical model with the selected mutation rate, crossover rate, and the maximum number of populations. The initial iteration for case 2 is shown in Figure 28.

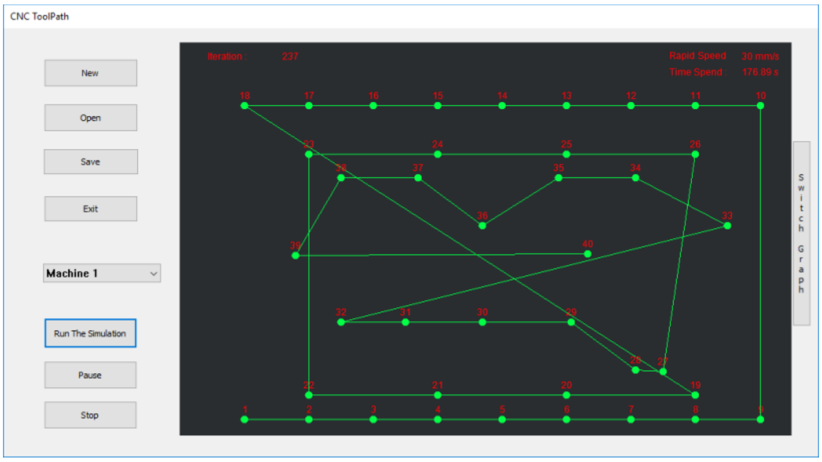

Figure 28: Initial toolpath sequence generated after 237 iterations

After 237 iterations, the total non-productive time calculated based on the generated sequence was 176.89 seconds. After the 2076 iterations, the toolpath sequence has been improved into the shortest path with a total time of 164.589 sec. This is shown in Figure 29.

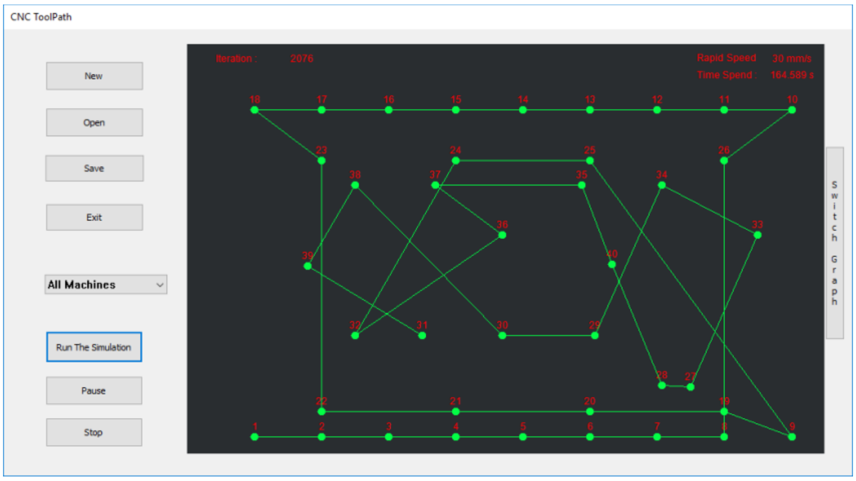

Figure 29: Improved toolpath sequence generated after 2076 iterations

The optimal toolpath was found after 6711 iterations. The time was 176.89 seconds, which gradually decreased to 164.589 seconds at the 2076th iteration. After 6711 iterations, the optimal toolpath sequence is obtained with 163.005 seconds. This is shown in Figure 30.

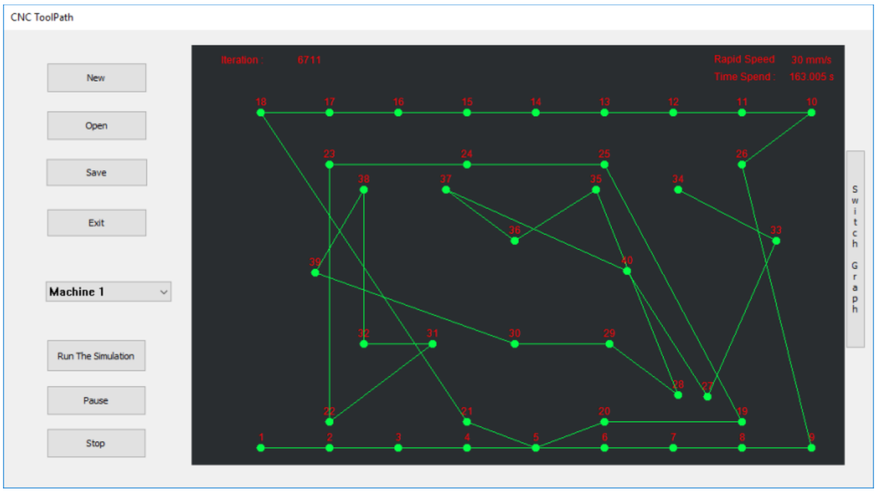

Figure 30: Optimal toolpath sequence generated after 6711 iterations

The optimal operational sequence generated by the proposed simulator Table 8.

Table 8: Optimal toolpath sequence for case 2 generated by the software

Operation	**Machine**	**Tool**	**Optimal Time Spend**
1	M1	1	163.0052
2	M1	1	
3	M1	1	
4	M1	1	
6	M1	1	
7	M1	1	
8	M1	1	
9	M1	1	
26	M1	1	
10	M1	1	
11	M1	1	

Table 8: Optimal toolpath sequence for case 2 generated by the software (continued)

Operation	Machine	Tool	Optimal Time Spend
12	M1	1	
13	M1	1	
14	M1	1	
15	M1	1	
16	M1	1	
17	M1	1	
18	M1	1	
21	M1	1	
5	M1	1	
20	M1	1	
19	M1	1	
25	M1	1	
24	M1	1	
23	M1	1	
22	M1	1	
31	M1	2	
32	M1	2	
38	M1	2	
38	M1	2	

The optimal toolpath sequence developed is obtained by minimizing the tool switching and airtime. The same workpiece is also simulated in Nx modelling and simulating software. The results from Nx software are shown in the Figure 31 and Figure 32.

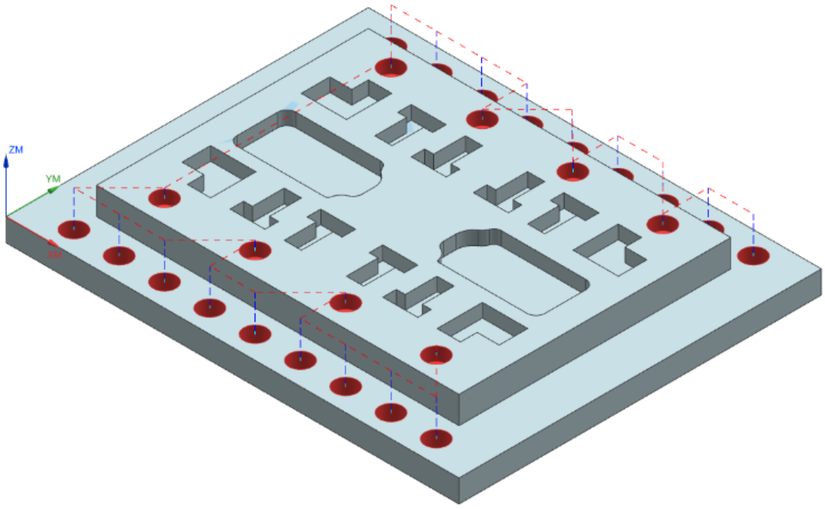

Figure 31: Shortest drilling toolpath generated on the workpiece with multiple holes

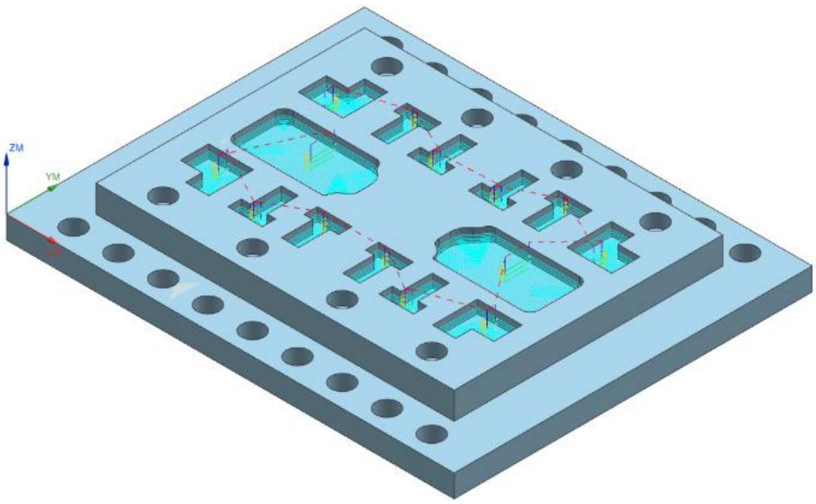

Figure 32: Shortest pocket cutting toolpath generated with multiple pockets

Figure 31 and Figure 32 show the shortest drilling path and pocket cutting path, respectively. For hole drilling operations, starting and endpoint for any operations will be the same, whereas the start points and end in the pocket milling operation will be different.

5.1.3 Case 3 - Two machines - Multi cutting tools - Single plane

For case 3, initial machining parameters are given to the GUI of the developed simulator as follows and shown in Figure 33.

Rapid speed :30 mm/sec

Tool switching point: (0, 0, 100)

Safe distance: (0, 0, 50)

Cutting tool change time: 30 seconds

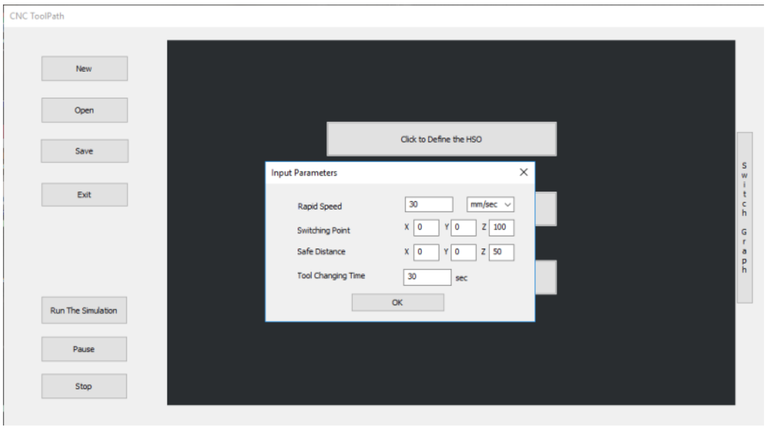

Figure 33: Input parameters in GUI for case 3

The simulator initiates the simulation with the machining data, operation sheet, and constraints table. The program runs with a proposed mathematical model with the selected mutation rate, crossover rate, and a maximum number of populations. Initial iterations for case 3 are shown in the following figures. The toolpath map for machine 1 and machine 2 after 100 iterations are shown in Figure 34 and Figure 35.

Greenline: Represents the cutting toolpath in machine 1

Redline: Represents the cutting toolpath in machine 2

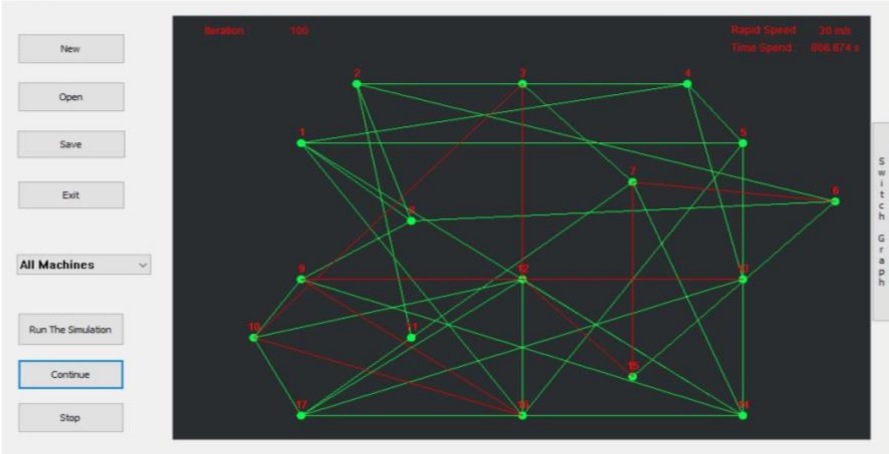

Figure 34: Simulation window of proposed CNC optimizer program on iteration 100

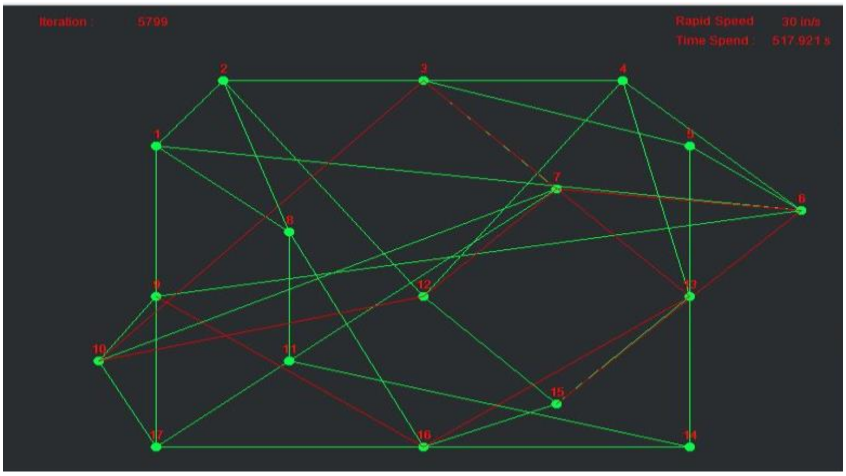

Figure 35: Optimal toolpath simulation results after 5799 iterations

The initial time in simulation shows the value of 1100 seconds, which is further reduced to 517.92 seconds after 5799 iterations. The computational program stops after obtaining the optimal path sequence with minimal time. The time vs the number of iteration graph is shown in Figure 36.

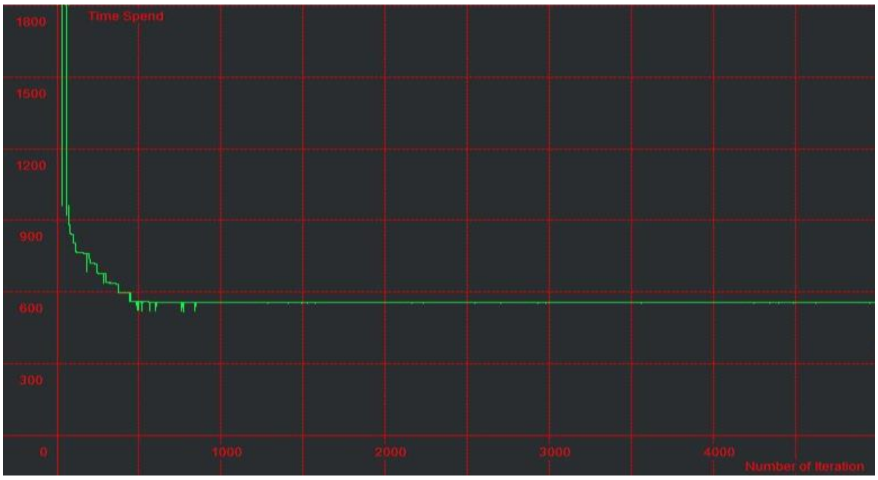

Figure 36: Number of iterations vs time graph for optimal sequence

The computational program shows the results with an optimal sequence in 2M with corresponding cutting tools. The optimal time was 1100 seconds, which gradually decreased to 806.87 seconds at the 100th iteration and reached the optimal time. After 5799 iterations, the optimal toolpath sequence is obtained in 517.92 seconds. The total non-productive time, including airtime and tool switching time in 2M are calculated here. The optimal operational sequence generated by the developed program is shown in Table 9.

Table 9: Optimal toolpath sequence for case 3 generated by the software

Process No.	**Machine**	**Tool**	**Process No.**	**Machine**	**Tool**	**Process No.**	**Machine**	**Tool**
3A	M1	1	11A	M1	1	17C	M1	7
7A	M1	1	10B	M1	5	14C	M1	7
4A	M1	1	3B	M1	5	5C	M1	7
5A	M1	1	17B	M1	2	1C	M1	7
6A	M1	1	16B	M1	6	2B	M1	3
13A	M1	1	13B	M1	6	4B	M1	3
14A	M1	1	9B	M1	6	13C	M2	8
15A	M1	1	8B	M1	3	16C	M2	8
16A	M1	1	11B	M1	3	9C	M2	8
17A	M1	1	12B	M1	4	10C	M2	3

Table 9: Optimal toolpath sequence for case 3 generated by the software (continued)

Process No.	**Machine**	**Tool**	**Process No.**	**Machine**	**Tool**	**Process No.**	**Machine**	**Tool**
10A	M1	1	7B	M1	4	3C	M2	3
9A	M1	1	6B	M1	4	12C	M2	7
1A	M1	1	15B	M1	4	7C	M2	7
2A	M1	1	14B	M1	2	6C	M2	7
8A	M1	1	5B	M1	2	15C	M2	7
12A	M1	1	1B	M1	2	Optimal airtime:517.92 sec		

5.1.4 Case 4 - Six machines - Multi Cutting Tools – Multi Planes

For case 4, initial machining parameters are given to the GUI of the developed simulator as follows and shown in Figure 37.

Rapid speed :30 mm/sec

Tool switching point: (10, 10, 100)

Safe distance: (0, 0, 70)

Cutting tool change time: 40 seconds

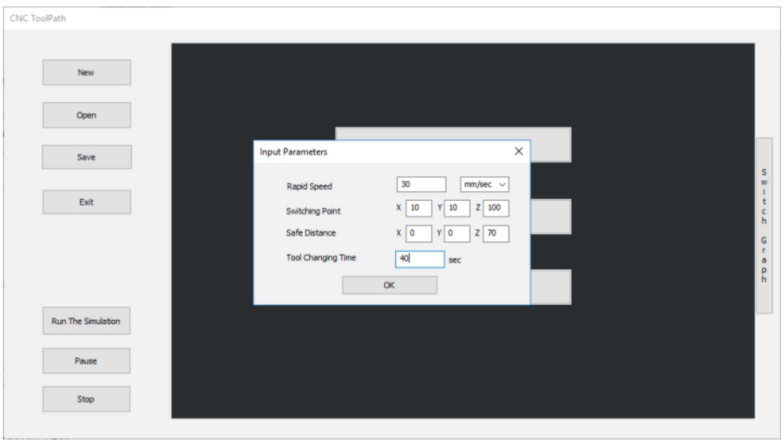

Figure 37: Input parameters in GUI for case 4

The simulator initiates the simulation with the machining data, operation sheet, and constraints table. The program runs with the proposed mathematical model with the selected mutation rate, crossover rate, and the maximum number of populations. The iterations for case 4 is shown in Figure 38, Figure 39, Figure 40, Figure 41 and Figure 42.

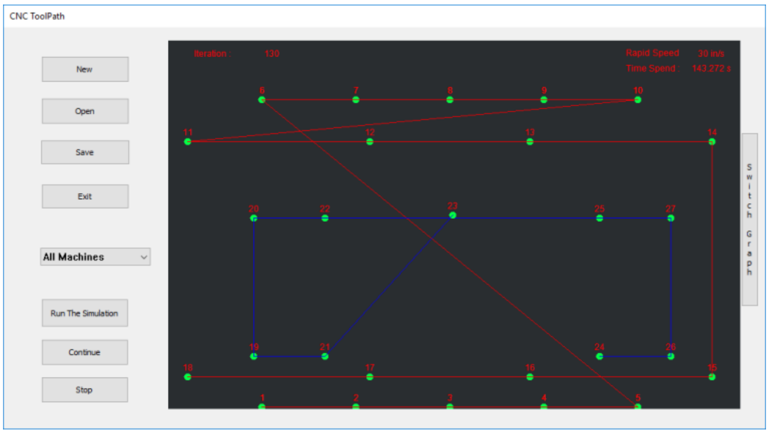

Figure 38: Simulation window of CNC optimizer program on iteration 130

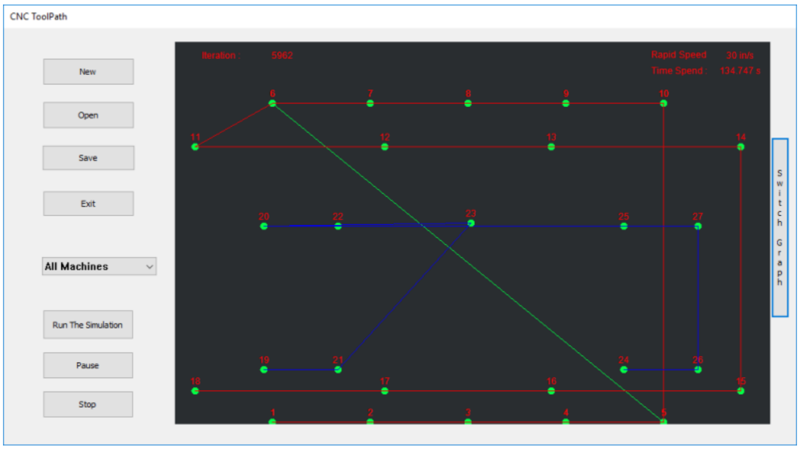

Figure 39: Optimal toolpath simulation results after 5962 iterations.

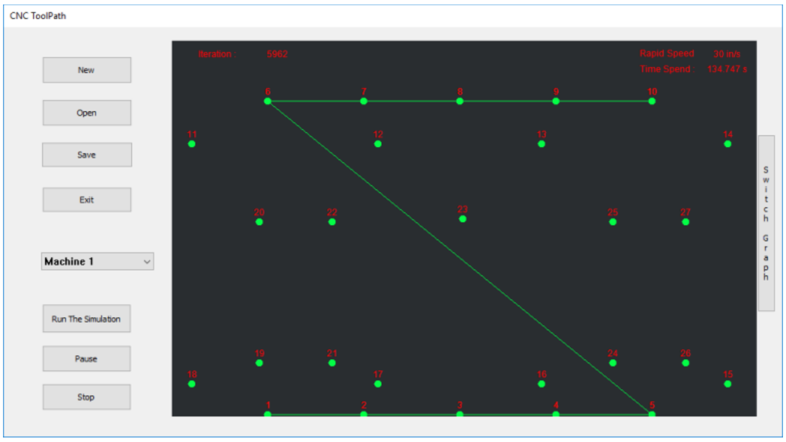

Figure 40: Optimal toolpath simulation results for M1

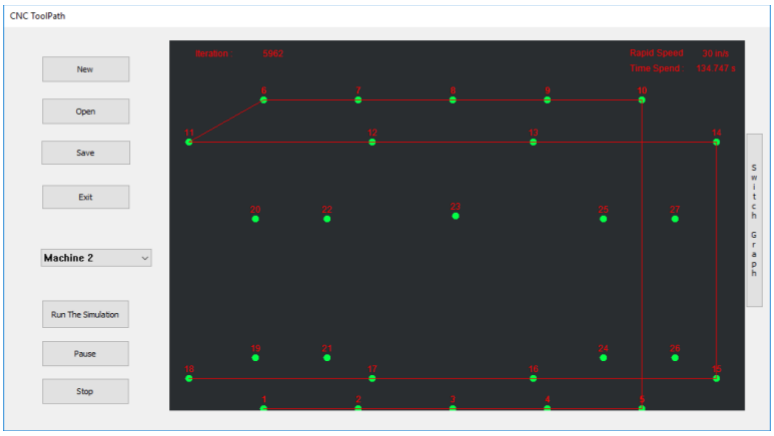

Figure 41: Optimal toolpath simulation results for M2

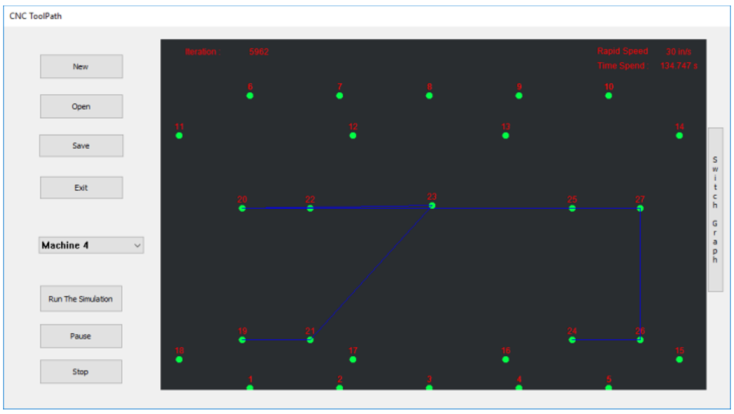

Figure 42: Optimal toolpath simulation results for M4

As per the simulation results, the optimal machining sequence is done by three machines out of six. Here unwanted machine switching is minimized. The final output sequence is shown in Table 10.

Table 10: Optimal toolpath sequence for case 4 generated by the software

Process No.	Machine	Tool	Process No.	Machine	Tool	Process No.	Machine	Tool
1A	M1	1	10B	M2	7	27	M4	5
2A	M1	1	9B	M2	7	25	M4	5
3A	M1	1	8B	M2	7	22	M4	5
4A	M1	1	7B	M2	7	20	M4	5
5A	M1	1	6B	M2	7	23	M4	5
6A	M1	1	11	M2	9	21	M4	5
7A	M1	1	12	M2	9	19	M4	5
8A	M1	1	13	M2	9			
9A	M1	1	14	M2	9			
10A	M1	1	15	M2	9			
1B	M2	7	16	M2	9			
2B	M2	7	17	M2	9			
3B	M2	7	18	M2	9			
4B	M2	7	24	M4	5	Optimal airtime:		
5B	M2	7	26	M4	5	134.746994018555		

Chapter 6: Conclusions

This research was focused on the toolpath optimization problem by selecting the optimal toolpath sequence in a multi production line. A new mathematical was developed and software with h user-friendly GUI is created for finding the optimal sequence. Developed software with the Hybrid GA-mTSP technique shows better results than the existing optimizing methods. For a single machine unit with multiple cutting tools and working planes, the optimal nonproductive time was achieved by eliminating unwanted tool switches in the single machine unit. During initial iterations, the total nonproductive time was high, and the optimal results show a 30% reduction in time. Various workpiece conditions are considered and analyzed by the developed model. For an infinite production line with multiple cutting tools and machine units, there was no such software available in the open-source market. Here, the optimal tool and job sequencing were obtained by minimizing the cutting tool switches inside one machine and within multiple machine units. This also benefits the cost-effective large-scale production by minimizing the buffer size.

Chapter 7: Future research

The developed technique can be implemented in various product manufacturing systems.

- In this work, the optimal toolpath sequence is generated. This sequence can be converted into corresponding G-Code, and M codes and directly feed into the controlling system.
- Incorporation of this technique into existing CAM packages.
- Human efforts and errors can be reduced by artificial intelligence tools and predictive models.

Advanced manufacturing techniques developed recently like Additive Manufacturing (AM), Laser Cutting, Robotic welding, etc., can be beneficial by this modified mathematical modelling. In future research, the proposed algorithm will apply to the following applications. 3D printing of buildings, aerospace parts manufacturing, Production line systems with multiple CNC units, Multi spot welding, IC Chip insertion units, Punching Holes, Job sequencing etc.

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List of Publications

[1] T. Ahammed, J. A. Qudeiri, A.-H. Mourad, A. Ziout, and F. Safieh, “Intelligent Sequence Optimization Method for Hole Making Operations in 2M Production Line,” in *Proceedings of ICETIT 2019*, pp. 339-355, Springer, 2020.

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Genetic Algorithm and a modified TSP algorithm were used to find the optimal toolpath for an infinite machine production line system. This proposed mathematical model is coded with a C++ program, and user-friendly software has been developed in this study. It was found that the total production time for multiple machining operations was significantly reduced with this technique by eliminating the unwanted cutting tool switches in the machine unit and between multiple machines. The approach could be useful in real-time manufacturing process outlines.

Thanveer Ahammed received his Master of Science in Mechanical Engineering from the Department of Mechanical and Aerospace Engineering, College of Engineering at United Arab Emirates University, UAE. He received his BSc in Mechanical Engineering from the Ilahia College of Engineering and Technology, Mahatma Gandhi University, Kerala, India.