

# The Development of a Storage Tank Automated Design and Analysis Framework (STADA)

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## *Abstract*

This paper presents an automated design and analysis framework for the development of a commercial rotationally molded storage tank (STADA). The framework integrates parametric modelling for the development of the geometric models, finite element analysis software for the structural assessment of the tank design concepts and a genetic algorithm for the evaluation, evolution and selection of the “best” design that meets the manufacturers/customers requirements. The methods developed here were able to produce and analyse 20 individual product designs over 5 generations in under 2 hours. The integration of a genetic algorithm enables the system to evaluate and select the ideal design concept in each generation and evolve the design parameters over the next generations to review all possible designs in a quick and efficient manner.

In rotational moulding, the wall thickness has a direct impact to the amount of material used and thus the amount of plastic waste associated with the process. The exploitation of these technologies and methods for the design and analysis of rotationally moulded storage tanks means that engineers and manufacturers can produce a design concept that has a consistent wall thickness throughout the design while maintaining the strength of the product. If these storage tanks can be designed with features that can maintain a more consistent wall thickness throughout the product and maintain the strength requirements, then manufacturers can reduce their plastic waste.

The focus of this paper is on the development of the integrated design and analysis framework with a brief example at the end that showcases how this powerful technique can be used to solve real world problems.

*Key Words: Innovative Manufacturing Processes and Practices, Industry 4.0 Technologies, Polymer Engineering Technologies.*

## 1. INTRODUCTION

Storage tanks have applications for storing a range of substances such as organic liquids, non-organic liquids, vapours and gases. They can range in size from 2-6m holding upwards of 75,000 litres, requiring a good combination of stiffness and impact (see Figure 1). They are typically cylindrical but can be rectangular or spherical in form.



Figure 1 - Example of some of the common storage tank designs in the commercial market from DESO Engineering 1900 litre single skin tank (left) and 5000 litre banded oil tank (right) (<https://desoengineering.co.uk/>)

There are many standards and regulations associated to the design and operation of storage tanks dependent upon what the tank is storing (e.g., oil) and where the tank is stored (e.g., above ground). As storage tanks are basically hollow thin structures, they are ideal candidates for the manufacturing process rotational moulding. Originally developed in the 1940s, rotational moulding is one of the most popular methods of manufacture for hollow plastic products (Crawford, 2020). The process involves pouring a fixed amount of plastic powder into a metal mould, which is then rotated perpendicular around two axes and heated in an oven thus melting the powder and coating the interior walls of the mould with molten plastic (Crawford, 1996). In order to produce an even wall thickness, the mould is continuously rotated even during the cooling stage. This method has many benefits. For example, it does not require any pressure, meaning the moulds can be made from sheet metal or CNC machined which helps reduce tooling costs. Another cost-effective benefit is that rotational moulding produces only a minimal amount of waste. This is due to the fact that only a specific amount of powder is measured and used to make the part with the desired wall thickness. However, the distribution of wall thickness is affected by many properties associated with the manufacturing process, they include heat transfer rates, the ratio and rates of rotation of the mould, mould wall thickness and material, powder characteristics (Crawford, 1996).

Rotationally molded parts are designed and dimensioned on only the outside surfaces that are in contact with the inside surface cavity of the mould. The inside of the moulded part will be free-formed and its size and shape will be dependent upon the outside size and shape, minus the wall thickness. The type of plastic material used and the thickness of the nominal wall determines the strength and loadbearing capability of the finished part. Although engineers may have a desired uniform wall thickness there is a slight variance in what can be achieved, this is often between +/-10% for commercial applications (Beall, 1998). Wall thickness uniformity is an important factor within rotational moulding. Increasing the wall thickness uniformity will result in a lower amount of material being required to manufacture the part, resulting in weight savings, energy and processing time improvements as well (Adams, 2018). These benefits all go towards manufacturers reducing their overall environmental impact within production.

With the increasing demand to improve the quality and reliability of products manufacturers are also now incorporating optimization methods (Guerrero, 2020). By adopting an evolutionary optimization technique such as a genetic algorithm within the design process a greater range of solutions can be explored to help determine the ideal design parameters to achieve the best measurable performance.

This paper focuses on the development of a new framework that integrates an automated design and analysis system with an optimization tool in the form of a genetic algorithm suitable for the development of a plastic storage oil tank. By doing so, the aim is to provide manufacturers with a system that can help determine the ideal design parameters for a tank that can withstand the structural load requirements and produce a uniform wall thickness thus reducing the amount of plastic consumption required for manufacturing the product resulting in both improvement product design and reduction of overall environmental impact.

## 2. METHOD

Figure 2 maps the framework used for the development of a storage tank. The process integrates a genetic algorithm within the design and analysis framework enabling the system to naturally evolve and explore numerous designs in each generation with the aim of selecting the best design concept that meets the requirements of the manufacturer/customer.

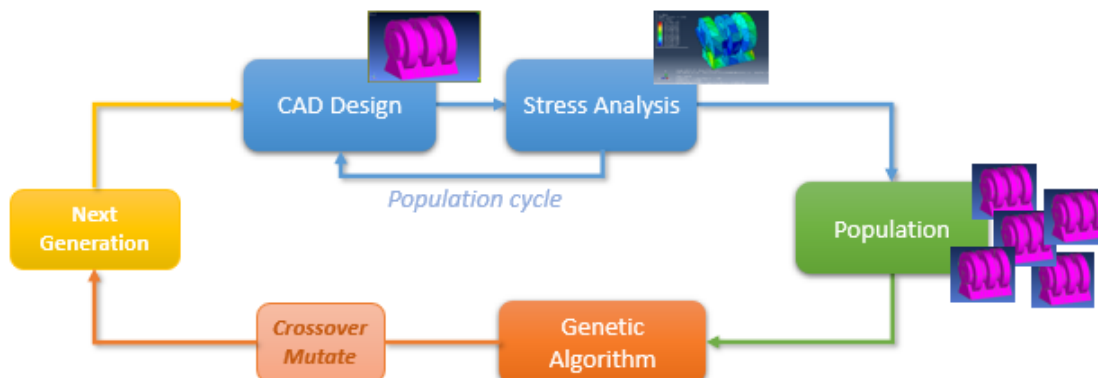


Figure 2 - Storage tank automated design and analysis framework

The process includes the automatic development of a CAD model based on critical features and dimensions. This CAD model of the storage tank then undergoes structural assessment in the finite element analysis system. Once the model is designed and analysed the results, along with key geometric properties are passed into the genetic algorithm for assessment. The GA measures each individual tank concept based on a fitness score, based on that score the best individual inside that population is determined and carried through to the next evolutionary cycle. The remaining members go into a tournament selection process for reproducing children for the next generation. This cycle continues until all generations are complete and the best individual of the entire evolutionary process is then established.

### 2.1. Storage Tank Design

The shape and placement of storage tanks can vary from cylindrical to rectangular, horizontally or vertically upright, and above or below ground placement respectively. For development purposes the work is focusing solely on fully enclosed above ground horizontally upright cylindrical tanks with flat bottoms. A critical design feature of a storage tank is its ribs.

The function of ribs on a storage tank is to protect against warpage by providing extra rigidity and strength. While it is desirable to have the walls as thin as possible the tank must also be strong enough to support the fluid load, this means that engineers often have to compromise between wall thickness and stiffness, and cost. Ribs can help achieve the same strength with thinner walls compared to having no ribs and thicker walls which also requires a longer cycle time and increased costs. The increase of stiffness provided by ribs is based upon the geometric properties of a rib, height and width of the rib, and the number of ribs, designers must balance the cost and potential weight increases with any associated strength improvements.

### 2.2. Computer Aided Design

A crucial element of this work was creating the relationship between the key physical features of the storage tank and the CAD functions required to model them. The key features on the storage tank are the main tank body including the dome ends, stiffener ribs and supporting feet. See figure 3.

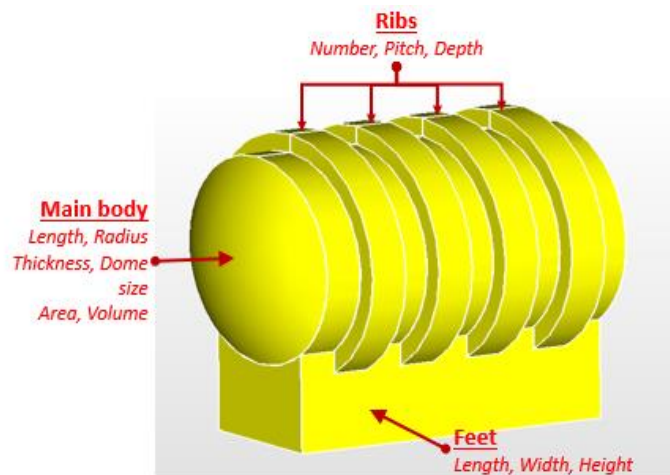


Figure 3 - Key features of the storage tank as identified within the system for modelling in the CAD environment.

With each of the primary physical features identified, the next stage in the process was to decipher the feature data and their spatial relationships with each other in a manner that enables the system to render a CAD model. Following this route means that once placed in the CAD environment all features within the design are related to their main component and the design intent remains intact. This process allowed for the system to establish a short list of key geometric properties that could be used to ascertain remaining design details. Thus, enabling both auto generation of geometry and evolutionary analysis to explore the effect the change of a small set of properties to generate a family of components within a population and set of generations.

### 2.3. Automated Design

Parametric modelling allows for the automatic update of the model should any parameters be modified, thus making it an ideal method for this automated design process and supports the incorporation of design intent into the design process. Design intent is the map from the design space to the design solution, it is “the set of functions which the system was designed to deliver in the anticipated operating environment” (Price, 2013). The tools and method of how a design is modelled in a CAD domain is important as it embodies the design intent of the component (Pratt, 2001).

The STADA framework has currently been developed in Microsoft Excel and Visual Basic Application. The main user input sheet shows the high-level breakdown of the 7 essential components required for the entire system to run. From this main sheet the user has control over the design process where they can either explore and evaluate the design space for a family of components or simply examine one particular design. When implementing the GA, the only section Users are required to work with is the genetic algorithm section. This section sets up the parameters for implementing the GA, it includes the population size, number of generations, mutation rate, fitness objective and measurement. The remaining sections can be used for single tank models, Users can see the effect of changing design and analysis parameters on a single individual design. The information on the main sheet has been kept to an absolute minimum while still providing users with sufficient control of the design process.

### 2.4. Finite Element Analysis

The integration of a finite element analysis (FEA) tool enables the STADA system to investigate the physical performance of a tank design, assessing whether the tank can withstand the conditions it is going to be exposed to while in operation. Today, there are many software vendors that provide simulation capabilities either in standalone software products like Abaqus or built-in packages in CAD programs such as SolidWorks or FreeCAD. Regardless of the tool being used, the analysis is always based upon the master CAD model and its geometry.

CADFix is a flexible CAD-to-CAE tool with ability to prepare the CAD models for any finite element analysis. The physical properties, material, mesh, loading and boundary conditions can be defined and assigned directly to the geometric model. The simulation model can then undergo analysis in the desired FEA system, and the results can be viewed back in the CAD domain thus providing one model that contains all CAD geometry information and its performance assessment.

### 2.5. Genetic Algorithm

A genetic algorithm consists of four main operations: fitness, selection, crossover and mutation. The GA starts from an initial population where each individual member represents a solution to the problem. Each member is then assessed using an objective function to assign a fitness score, the GA measures the quality of that member to others in the population. The principle of survival of the fittest is employed to explore the solution space to identify the best candidate either to carry forward into the next generation or simply select as the final solution to the problem (Khoie, 2010). Selection is applied to the current population to create an intermediate population for crossover and mutation to then create the next generation. Crossover models the exchange of genetic information whereas mutation models a random change within the genetic information. The intermediate population is used to couple individuals, representing them as parents to generate the offspring for the next generation. The offspring are reproduced by crossover the genes of the parents. Mutation can then occur on the entire population, the elite selection or solely the offspring, it guarantees a diverse population. The occurrence of mutation is what allows a GA the ability to explore previously unmapped design spaces.

## 3. RESULTS

This system was tested in three ways. Firstly, ability to automatically design and analyse a storage tank that can be rotationally moulded. Secondly, generating a family of components by randomly changing and mutating key design features across a population. Lastly, completing the genetic algorithm application to measure the performance of each design concept and evolving the product to meet a customer goal of maximising or minimising a quantity. Table 1 details the material and fluid properties employed in the testing.

Table 1 - Material and fluid properties employed in the testing of the tank designs.

Material	Youngs Modulus /MPa	Poisson Ratio	Material Density /kg/m <sup>3</sup>	Design Stress /MPa	Fluid Name	Fluid Density /kg/m <sup>3</sup>	Gravitational Acceleration /m/s <sup>2</sup>
High Density Polyethylene	959	0.34	958	20	Water	1000	9.81

3.1. An Individual Storage Tank Design and Analysis

Table 2 and Figure 4 show the results of this test. The plastic storage tank was modelled in CADFix software as shown in figure 4(a). Through the same CAD package, the system could automatically apply the mesh, material, loading and boundary conditions, and generate the input file to send to Abaqus for structural analysis, figure 4(b). The structural analysis of the tank was also automatically executed through Abaqus, figure 4(c), where the results are brought back into the CAD domain and analysed within the same geometric model from the first stage of the process, figure 4(d).

Table 2 - Results of the design of an individual storage tank

Part Name	Length /m	Height /m	Thickness /m	No. of Ribs	Rib Pitch /m	Max Volume /litres	Max Stress /Pa
Cylinder1	4	3	0.0055	3	0.57	28,274	369,848,064.00
<b>Total System Execution Time</b>							<b>2min</b>

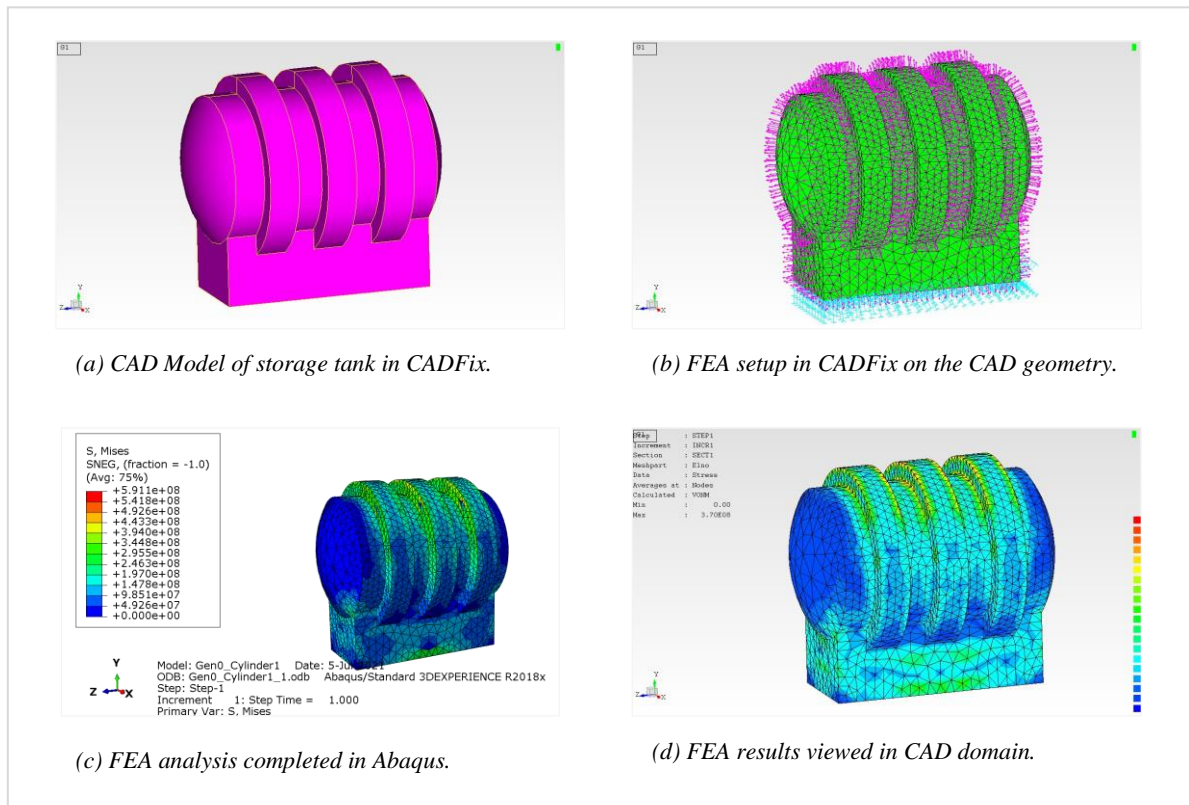


Figure 4 - Screenshots showing the results of the 4 key stages in the STADA system for the design and analysis of a storage tank.

3.2. A Population of Storage Tank Design Concepts and Analysis

Table 3 and figure 5 shows a few of the results from the population build. For an initial population, STADA generates designs by randomly selecting a value for length, height and number of ribs. From these initial values the system calculates all other lower-level design parameters for modelling and simulating the designs automatically.

Table 3 - Results of a set of individuals from inside the population

Generation	Part Name	Length /m	Height /m	Thickness /m	Number of Ribs	Max Volume /l	Max. Stress /Pa
1	Cylinder1	13.97	12.22	0.0359	1	1,619,250	5.6E+08
1	Cylinder10	5.37	4.09	0.0039	6	70,287	1.66E+09
1	Cylinder20	2.83	12.55	0.0379	1	345,866	5.8E+08
1	Cylinder30	16.38	20.45	0.1013	5	5,274,016	6.61E+08
1	Cylinder40	5.01	3.11	0.0025	7	37,936	1.34E+09
1	Cylinder50	14.7	6.2	0.0090	3	441,217	5.94E+08
1	Cylinder60	4.78	16.58	0.0664	5	1,015,551	6.23E+08
1	Cylinder70	11.3	2.19	0.0025	7	42,371	2.42E+08
1	Cylinder80	6.69	3.1	0.0025	5	50,331	9.02E+08
1	Cylinder90	20.14	20.3	0.0998	2	6,390,826	5.41E+08
1	Cylinder100	8.09	14.34	0.0496	2	1,288,585	4.15E+08

Population size 100  
Total System Execution Time 113min

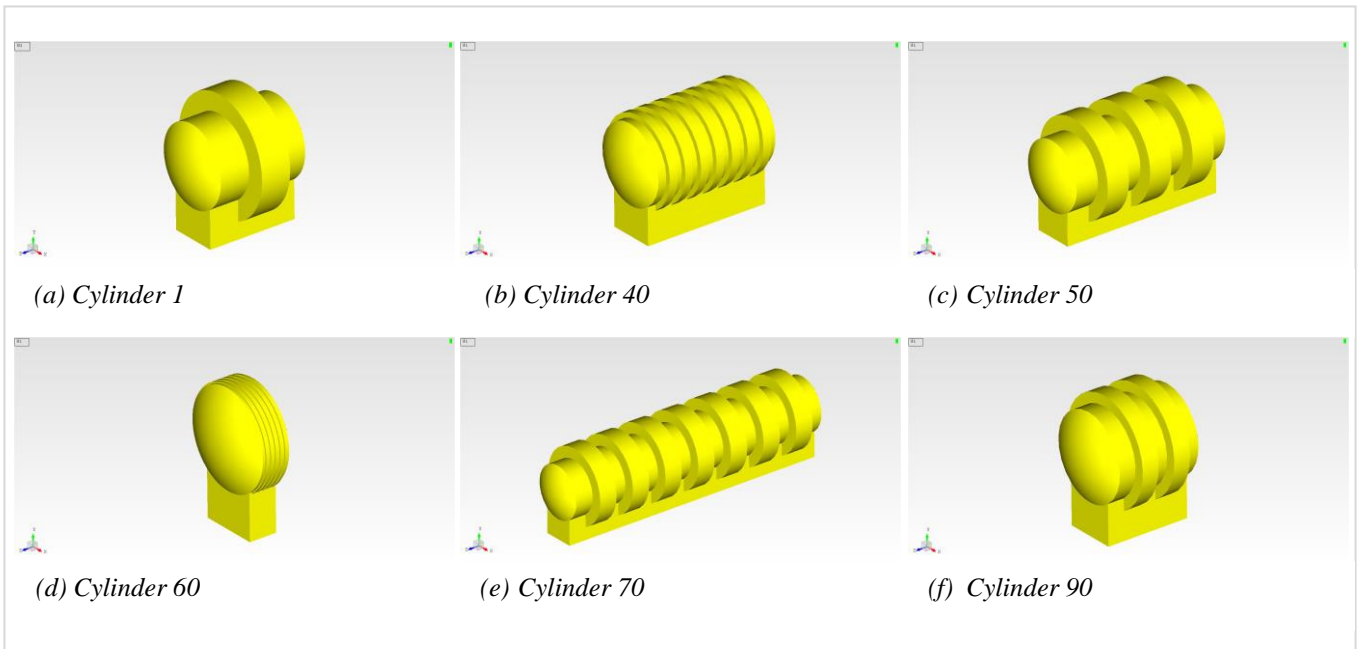


Figure 5 - A subset of the CAD rendered models of the storage tank from the population build.

### 3.3. Evolving Storage Tank to Meet Customer Goal

These early experiments with the genetic algorithm were intended to determine whether the system was capable of exploring and analysing an extended range of tank concepts and able to select the best design based on an initial simple goal.

#### 3.3.1. Maximising Volume

The first optimization procedure was done for maximising the amount of liquid the tank can store, i.e., maximising tank volume. In this instance the GA is only measuring one objective function, maximum volume, so the FEA analysis of the system can be discarded. This test was executed over 5 generations with a population size of 20, producing a total of 100 tanks in under an hour. This is a significant time improvement compared to how long it would take to manually model each design. The best individual design parameters for each generation can be viewed in the table below. The design parameters for each elite model did not change significantly throughout the evolutionary cycle, the first population randomly produced a model with parameters close to the upper design limits then from there the designs slowly evolved to improve the design where they could; increased height and decreased thickness.

Table 4 - Best individual from each generation for maximising the volume of the storage tank.

Generation	Part Name	Length /m	Height /m	Thickness /m	Number. of Ribs	Max Volume /l
1	Cylinder12	20.72	19.22	0.089	2	5,900,197
2	Cylinder3	20	19.855	0.0055	1	6,185,550
3	Cylinder1	20	19.855	0.0055	1	6,185,550
4	Cylinder11	20	20	0.0055	2	6,276,276
5	Cylinder1	20	20	0.0055	2	6,276,276

Population size 20  
 Number of generations 5  
**Total System Execution Time 52min**

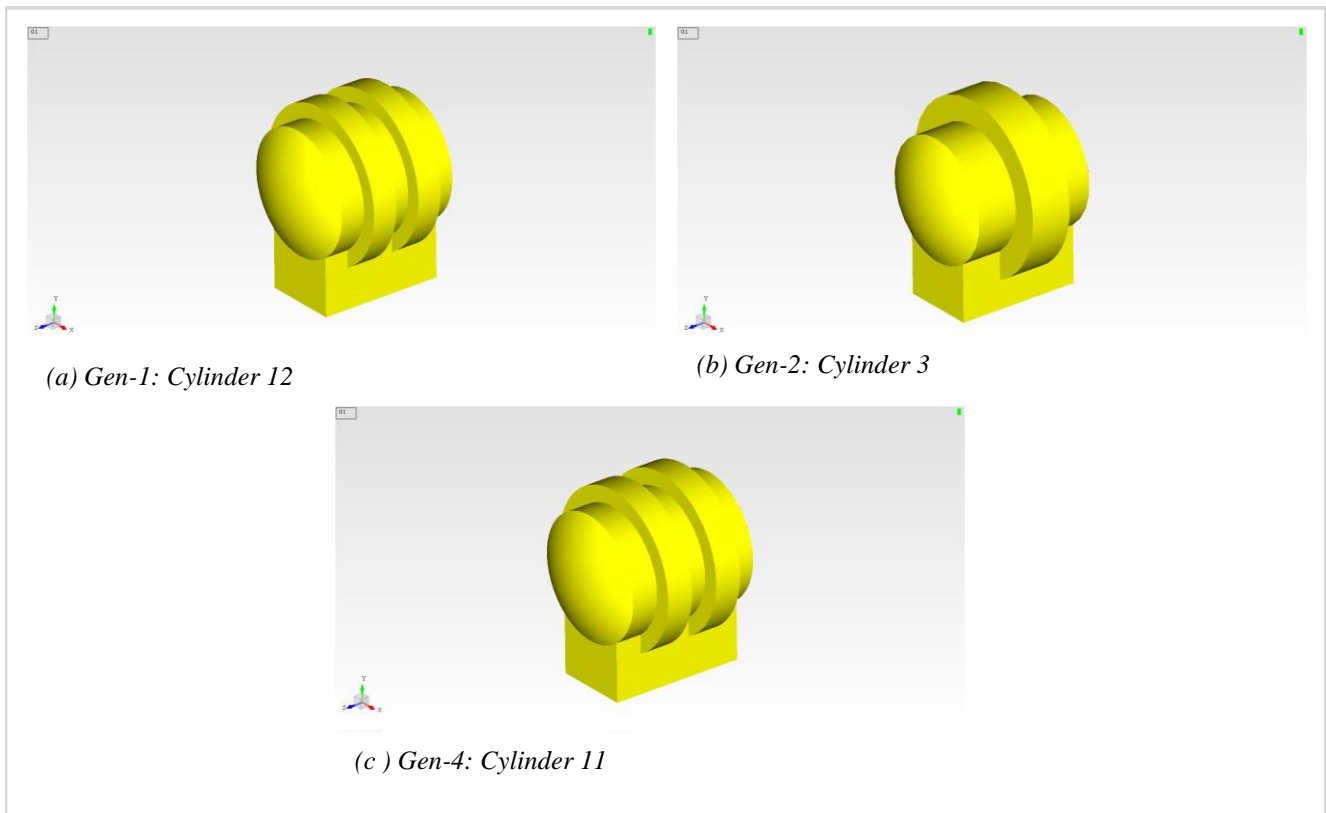


Figure 6 - The best storage tank design from five generations optimising the volume of the tanks.

### 3.3.2. Minimising Stress

Maximising the structural strength of the storage tanks is a desirable customer/manufacturer goal, thus the fitness function is switched to minimum CAD stress. The elite part (see Table 5) in the first generation is also the best component in the next two generations. By the fourth generation however, the design has evolved to produce a stronger tank where the stress has been minimised. Figure 7 shows the CAD model and stress results of these two design concepts. It is interesting to see that the strongest tank designs are those with no ribs when ribs are meant to increase the structural strength of a tank.

Table 5 - Best individual from each generation for minimising the stress of the storage tank.

Generation	Part Name	Length /m	Height /m	Thickness /m	Number. of Ribs	Max Stress /Pa
1	Cylinder6	20.24	18.43	0.0822	0	38,783,420
2	Cylinder1	20.24	18.43	0.0822	0	38,783,420
3	Cylinder1	20.24	18.43	0.0822	0	38,783,420
4	Cylinder2	9.685	4.855	0.3773	0	23,727,746
5	Cylinder1	9.685	4.855	0.3773	0	23,727,746

Population size 20  
 Number of generations 5  
**Total System Execution Time 102min**

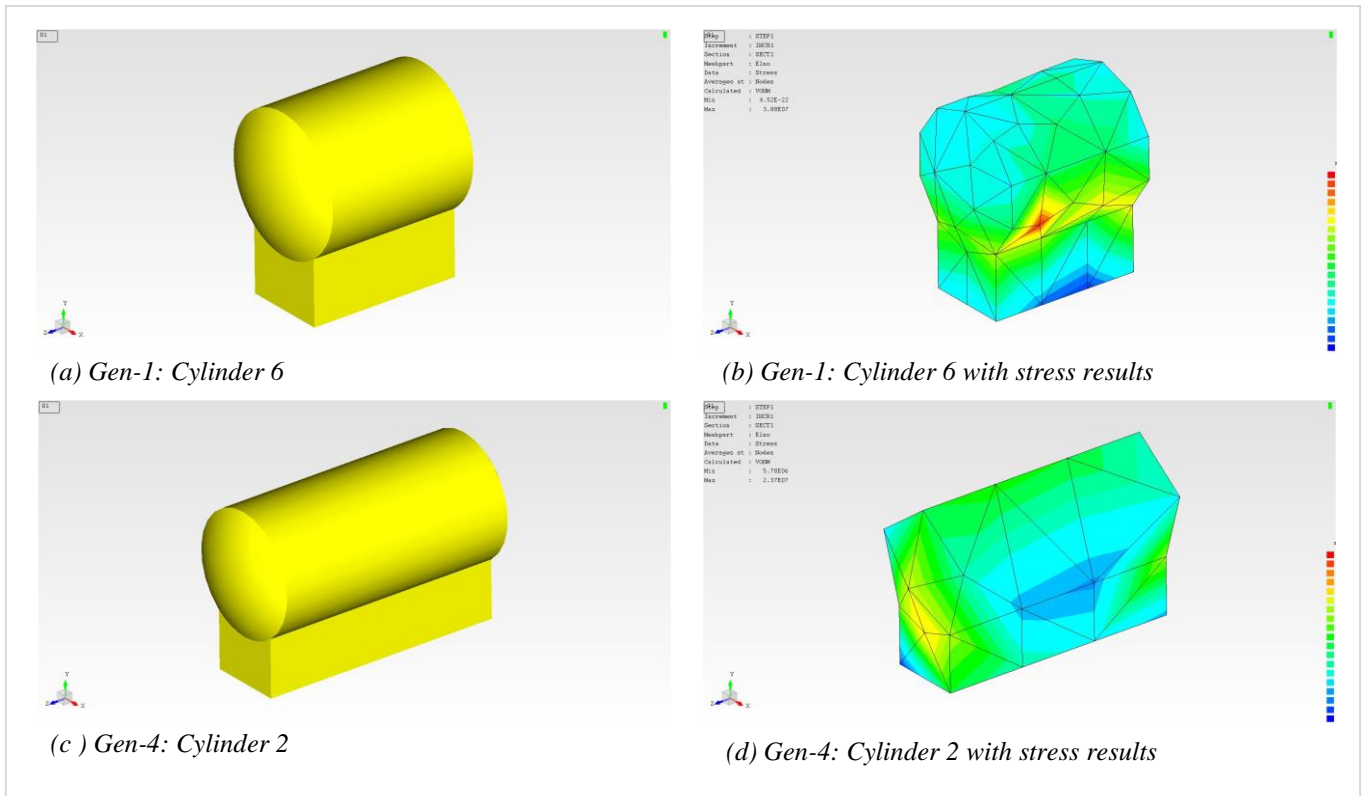


Figure 7 - Best two design concepts from the study on optimising the structural strength of the storage tank.

#### 4. DISCUSSION

This work successfully created an automated design and analysis process to develop a storage tank fit for the manufacturing process rotational moulding. It effectively incorporated a genetic algorithm to optimise the design concepts for the tank, exploring generations of design solutions that would minimise or maximise the performance parameters of the tanks. The process was able to produce a single CAD design and FEA simulation in 2 minutes and then go on to produce a family of 100 in under 2 hours. The time benefits demonstrated by the STADA framework would provide a significant time improvement to the current design practice.

The design process follows the basic principles in rotational moulded storage tanks. However, despite consideration of the manufacturing process in the early stages of development the system has yet to apply some of the key manufacturing details within the design process itself. The purpose of focusing on rotationally moulded storage tanks was to provide the application with a real-world engineering design and manufacturing problem to solve. The problem many rotational moulders face is being able to produce a strong fit-for-purpose yet as thin as possible product with uniform wall thickness. Wall thickness in rotational moulding is the main component of how much plastic is both utilised and wasted during manufacture. The distribution of wall thickness is affected by properties associated with the manufacturing process itself (e.g., heat transfer rates) and

those associated with the design concept. Sharp corners and draft angles are two particular design features on the storage tank that have a significant impact on the uniformity of the wall thickness. Corner radii on plastic parts helps distribute the stress over a broader area, strengthening the part, and ensures that the powders fuse evenly in and around the corners. Small-radiused corners or sharp corners will be the location of a stress concentration, creating a weak point on the component. In rotationally moulding, obtuse (or concave) external corners are usually closer to the heat source so material often melts quicker and sticks to these corners more resulting in thicker corners. For corners with really small radii, the powder material struggles to flow into the small corners as the mould rotates which results a thinner wall thickness and therefore in non-uniform wall thickness across the component. Similarly, adding a draft angle to design features such as ribs, recesses and holes will help the maintain a steady flow of material as the mould rotates during manufacturing and this in turn helps keep the wall thickness uniform. There are no set rules for what the draft angle or corner radii should be, there are some recommendations, but it is largely dependent on the design, the product and the manufacturer. Future development of STADA will focus on implementing these new design features, the GA can then be incorporated to assess various size variations across a range of design concepts and again determine the “best” design for the customer.

As well as improving the design process, the work will look at including multi-objective function into the GA. This would allow the system to optimise the design against multiple criteria, particularly minimising the wall thickness while maximising the volume and strength of the storage tank. After completing these new developments, STADA will be able to provide manufacturers with a system that can help determine the ideal design parameters for a tank that can withstand the structural load requirements and produce a uniform wall thickness thus reducing the amount of plastic consumption required for manufacturing the product resulting in both improvement product design and reduction of overall environmental impact.

By combining parametric design methods with simulation analysis and an optimisation tool, this work was able to successfully evaluate, evolve and select the “best” design to achieve the customer’s goal.

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