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Composites Product and Process Quality

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Abstract

This paper studies the quality characteristics of composite products and processes related to the airplane parts. The identified quality characteristics are: materials related, process parameters related. The material related characteristics are material's expiration date, porosity, and material thickness. The process related characteristics are related to the process failures, and those are: thermo couple failures, vacuum bag burst, improper vacuum bagging, high pressure, and improper cure. Data is collected from the production line and analyzed via quality tools to identify the most important causes and their consequences and suggest solutions that could improve the quality and save the company on the cost of poor quality.

Keywords

Cost of Poor Quality (COPQ), fishbone analysis, FMEA, Pareto, quality characteristics

1. Introduction

The term of "Quality" represents the properties of products and/or services that are valued by the consumer. Quality of product and process is a key factor in any aircraft industry in order to provide good manufacturing performance. However, some aircraft components that being produced have problems in the standard specifications fulfillment. Nowadays, composite materials have an increasing demand in the industry such as automotive and aerospace industries; due to its superior advantages like high stiffness, high strength, corrosion resistance and fatigue resistance which help in providing light-weight, highly functional and dependable design [1].

On the other hand, and like every material, composites can be affected by fatigue and other damages. Damage of composite is usually in the form of delamination, which means fibers are broken due to impact, fatigue damage that affects the zone of composite materials via micro cracking, fiber laminations etc. Furthermore, damage in composites is invisible to the naked eye therefore; this is why a proper detection and evaluation are needed [2].

This leads the manufacturers and scientists to search more about this material and its benefits. In addition of understanding the main causes of the defects in order to improve the quality of the products produced using composite materials. Defects in composite materials can be found either during the manufacturing process or during the normal service life of the component [3]. These defects can be categorized into two groups: design induced defects and process induced defects [4]. Such defects affect the quality, performance and the cost of the produced products.

Manufacturing companies often contain composites defects in product and defects occur in the process itself. An example of composites defects is a delamination, and this is known as upon loading defects that can grow and coalesce leading to the separation of layers. This defect can significantly reduce the performance of laminate, and affect its residual strength and stiffness. Therefore, accurate modeling and evaluation of the influence of a delamination on damage initiation and growth in fiber-reinforced composite laminates under complex loading conditions is a primary design concern [5].

Porosity is another example of composites defects in product. It is the cavities or voids in the composite material, which can arise from improperly controlled manufacturing process such as improper air controlled during cure, loss of cure pressure or inadequate volatile gas bleed off from the resin. Furthermore, the wet storage area is one of the important causes of porosity.

The presence of porosity may do a strong influence on the mechanical properties of composite materials such as compressive strength, transverse tensile strength, and inter-laminar shear strength. All these influence can affect the overall strength and performance of the composite structure [6].

Other examples of composite defects in products are Foreign Object Damage (FOD) problem, thickness not according to drawing, core step and high volume of waste in bagging consumable materials etc.
The other type of defects that could affect the composites materials is process defects such as vacuum leak, material expired, thermocouple failure and temperate overshot. And most of these defects occur during the curing process.
A number of studies have been done to study the characteristics of the composite materials and to find the major causes of defects in composite sandwich structures parts. The results of these studies showed that for any composite structure the causes of failure are highly dependent on a range of design and manufacturing parameters including the geometry, material, lay-up, temperature, consolidation pressure, resin viscosity, loading conditions, load history and failure modes [7] [8].

The main purpose of the present study is to provide an objective characterization reasons and solutions for different composite defects. The paper deals especially with composite sandwich panels used in aerospace industry which are manufactured by dry manual composite lay-up. The main structure of these panels consists of carbon fiber prepreg and honey comb core. Two types of defects are investigated product defects and process defects. A data analysis has been done based on historical data collection.

2. Product and Process Data Collection

Historical data has been collected from an aerospace company and it was found that such companies face different types of defects in the process and in the products produced.

2.1 Defects in Product

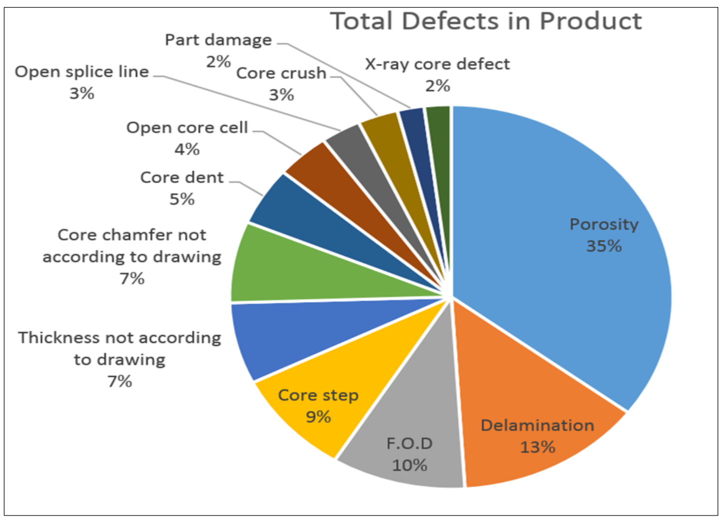


Figure 1. Causes of product defects

Figure 1 shows the causes of product defects and the percentage of each one of them. From this figure (Figure 1) it can be noticed that the majority of causes are as the following: porosity (35%), delamination (13%), FOD (10%), Thickness not according to drawing (10%), core step (9%) and high volume of waste in bagging consumable materials (7%). Therefore, this paper will focus on the six biggest causes.

2.2 Defects in Process

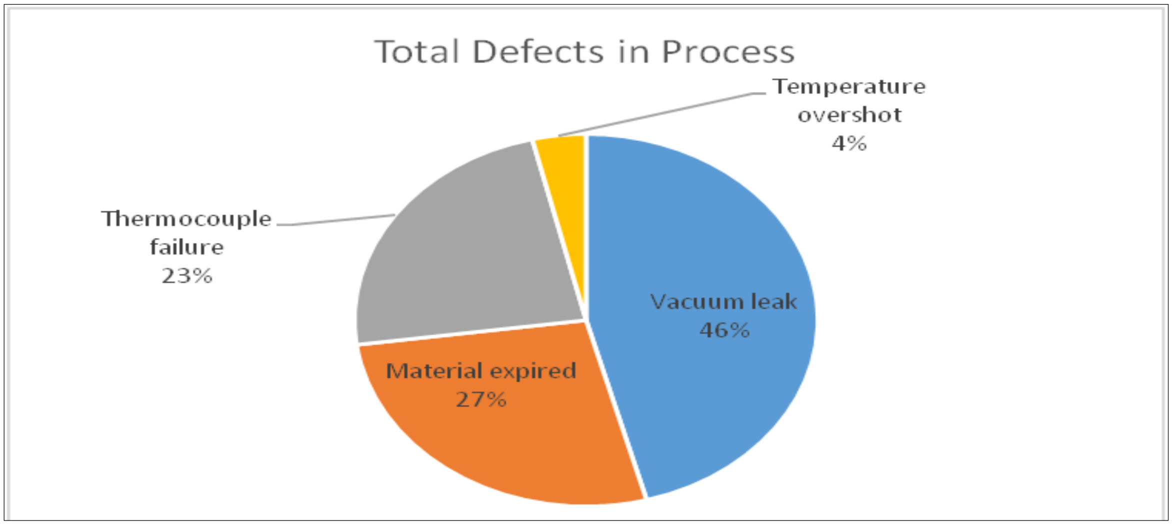


Figure 2. Causes of defects in the process

Figure 2 shows the causes of process defects and the percentage of each one of them. From this Figure 2 it can be noticed that the causes of defects are as the following: vacuum leak (46%), material expired (27%), thermocouple failure (23%) and temperate overshot (4%).

3. Data Analysis

A data analysis has been applied to study and highlight the areas of concerns using two powerful tools which are Pareto chart and quality control charts.

3.1 Pareto Chart

The main goal of this paper is to minimize the defects during the production process or in the product itself. A Pareto diagram which is also known as the "80/20 rule" is an analytical tool that is used to find the 20 percent of work that will generate 80 percent of the results that doing all of the work would deliver.
The following result has been found after studying the causes and number of defects in products:

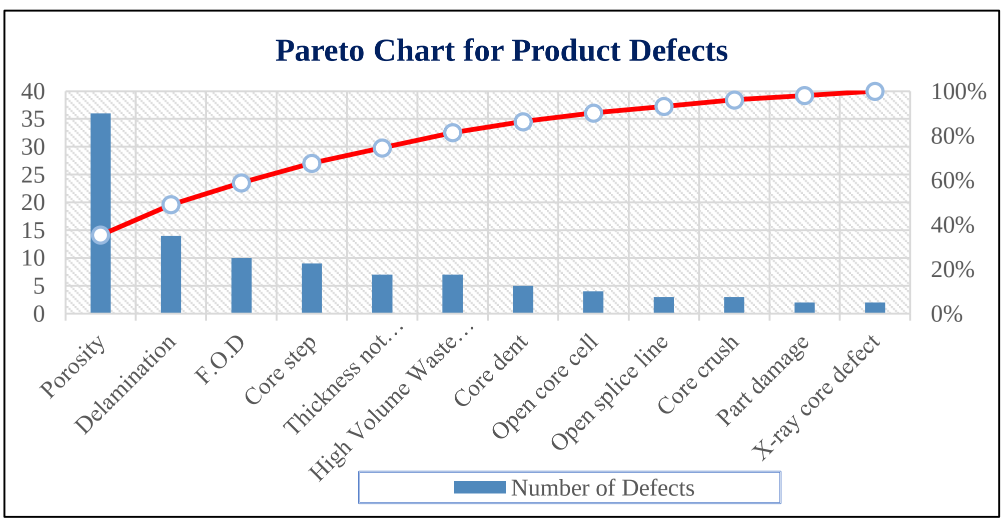


Figure 3. Pareto chart for product defects

Figure 3 above shows that the company will get the biggest benefits by providing good methods and solutions to solve the problem of porosity. Once this is done, it may be worth looking at suggested improvements to overcome the problems of delamination and FOD.
On the other hand, the causes and number of defects in processes were studied and pareto chart was plotted as shown in the figure below:

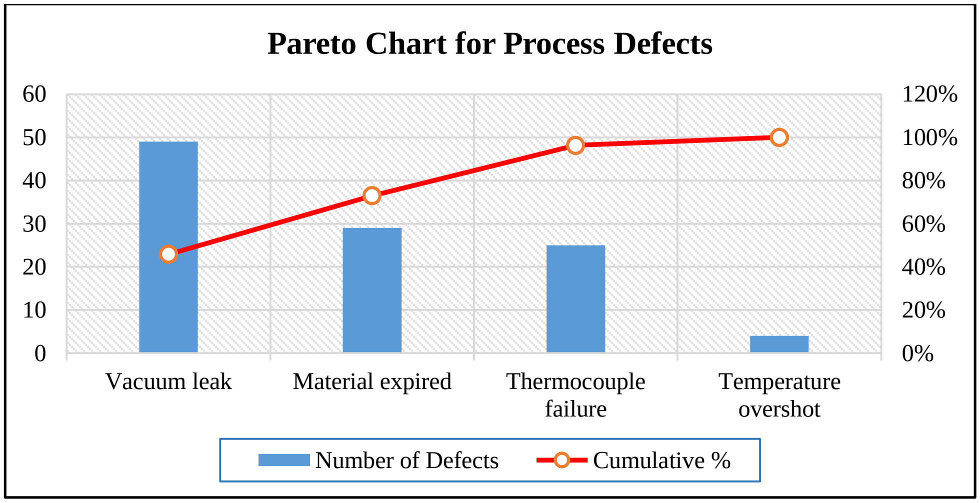


Figure 3. Pareto chart for process defects

As it is shown in Figure 4 above, such a company will get the biggest benefits in the process by providing good methods and solutions to solve the problem of vacuum leak. Once this is done, it may be worth looking at suggested improvements to overcome the problems of material expired and thermocouple failure.

3.2 Quality Control Charts

The product and process quality control was studied. The products data of five months in 2014 were studied and analyzed to understand the product defects behavior. The total number of observations have a size of 918 parts (6 parts per day) distributed on 153 days. Two p-charts were constructed to the number of products and process defects per day where represented by two p-charts.

P-chart of number of product defects per day

The control limits were calculated as: $LCL = \overline{p} - z\sqrt{\dfrac{\overline{p}(1-\overline{p})}{n}}$, $UCL = \overline{p} + z\sqrt{\dfrac{\overline{p}(1-\overline{p})}{n}}$

The parameters and the p-chart based on (sigma level 3) are shown below:

Input	
No. of samples	153
Sample size	6
Sigma level	3

Output	
$\overline{p}$ =	0.11
UCL =	0.50
LCL =	0.00

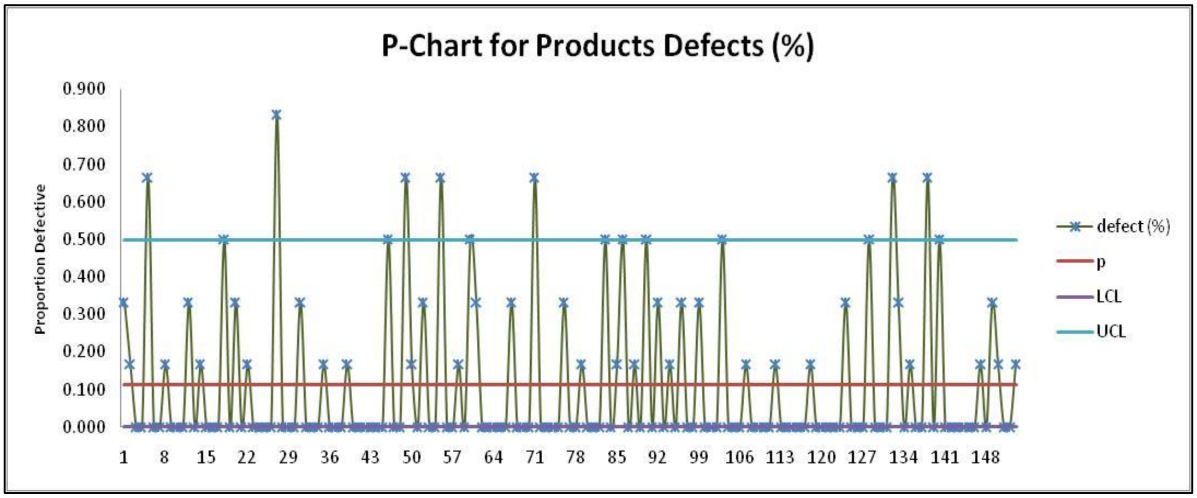


Figure 5. P-chart for product defects

Figure 5 shows that, there are 9 signals touching the upper control limit and there are 7 out of control signals. As the lower control limit was a negative, we considered it as zero. It also shows a trend in the defects which may cause the process to be out of control in the future. Process is not stable, which is leading to none consistence quality.

4. The Quality Characteristics

A key characteristic is defined as "the feature of a material or part whose variation has a significant influence on the fit, performance, service life or manufacturability" of the product. These characteristics should be measured and have value for the customer.

4.1 Product Efficiency

Products efficiency is tracked by the first article inspection and products non-conformances. The data included in this study is linked to results of those inspections verification process.

- **First Article Inspection**

First article inspection is surveillance verification of physical and individual characteristics. It ensures all engineering, design requirements and specification have been fulfilled. FAI proves that all processes and equipment used for a serial production can provide consistently the required product quality.

- **Products Non-Conformances**

Non-conformances system is an in-process inspection followed to manage the part performances. It's performed for the different production operations to monitor quality non-conformances.

4.2 FOD Control

It's very important to ensure that the company monitors and controls the production line from foreign object debris to prevent any FOD from getting in production zone. FOD at any aerospace factory can cause damage that costs millions of Dollars every year. Most aerospace companies apply the following procedures to reduce FOD within the facility:

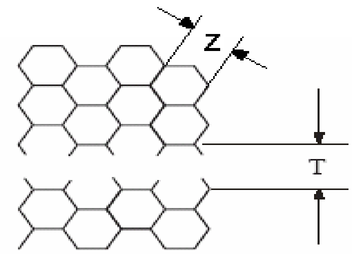
- Training program for FOD-prevention
- Facility inspection.
- Facility maintenance.
- Coordination with all affected parties regarding FOD and its effects.

4.3 Monitoring of environmental influences

The work place environment has to be fully monitored, in order to produce high quality products. The two main factors to monitor the environmental influences are temperature and humidity. Temperature needs to be maintained between 18°C and 24°C, while humidity needs to be maintained between32% RH to 54%.

4.4 Honeycomb core Inspection

The Honey combs for all projects are received from suppliers as kits. In the layup procedure the operator has to ensure that they are following the requirements as shown below. Where the distance between one core and the other should not exceed the required amount.



Cell width (Z) (mm)	Thickness-max (T) (mm)
3.17	3.17
4.76	4.76
6.35	4.75
9.52	6.35

Figure 6: Hexagonal Honeycomb structure

4.5 Compaction Level

The compaction level is different for the monolithic and sandwich parts where the vacuum level for all carbon under core is 100%, it’s 30% for all carbon steps after core. None compliance to those compaction levels will cause defects.

4.6 Cure Cycle

The temperature, pressure and vacuum in the cure cycle have to be controlled according to the customers’ requirements. Temperature has to raise according to the heating rate. 1-3°C per minute below 160°C, and 0.5-3°C per minute above 160°C. Higher temperature cure rates causes issues with volatiles and air expansion. Pressure to 3 bar +/- 0.2 bar and any amount above that will result in porosity. Vacuum -30kPa +/- 5kPa and any amount below that will result in a defective part.

5. Proposed Improvements

Failure Mode and Effects Analysis (FMEA) have been implemented on the different failure modes of composite and several suggestions have been purposed to the composite manufacturing companies. Table 1 lists those proposed solutions.

Table 1. Suggested solutions for product defects

Defect	**Causes**	**Suggested Solutions**

Porosity	• Vacuum pressure between the resins (air not properly controlled during cure). • Vacuum leak and loss of vacuum due to improper vacuum bags fixing during lay-up process • Wet storage area	• Evacuating the air between the resins from more than one place to ensure that the parts of product without or with less porosity volume. • Extensive training of staff to ensure that vacuum bags are properly fixed during lay-up process. • Using dry storage area wherever the resin exists. So the relative humidity should be maintained on a specific value.
Delamination	• Improper compression because of poor laminating technique. • Air bubbles between the layers. • FOD during lay-up process could cause delamination such as any abject matters ingress into laminate like hair, piece of paper and wood cutters.	• Applying pressure continuously from the center of the layer to the edges, and this can be done by using roller. • Layers must be dried properly because some of the liquids will be mixed with the resin and create air bubbles. • Layers must be cleaned from any contamination before pouring the resin, this will strengthen the bonds between layers.
FOD	• Employees are not covering their hair. • Employees are not wearing special shoes while working in the clean room. • The material of the uniform (overcoat) is not suitable for such work.	• Add some devices that alert once they find sensitive items before going to the next step. • Introduce new uniforms for the employees that cover the hair and all body parts. Any pocket should be closed with zipper to avoid any pen or any object to fall. • The staff should use special shoes (anti static shoes). • Companies should aware their staff about the quality issues.
Core Step	• The large number of splices can increase the possibilities of the presence of more cavities and openings during the vacuuming in the lay-up process. • High pressure can result in core shrinkage which will create a core step. • The inappropriate handling and holding of strips.	• Modification can be done to the design of composite sandwich so that the number of splices is reduced main while keeping the needed mechanical properties as they are to guarantee the strength of the sandwich. • Having proper setting of the grip strips to ensure proper handling and bagging. • Having more control and proper setting of the autoclave pressure by having controlled values and reach optimal values of the pressure that lessen the possibility of having shrinkage that could led to core step. • Automation of the lay-up process activities so that the human interactions that lead to human errors will be reduced to minimum.

Thickness not according to drawings	• Improper cure • Prepreg stretching in layup process	• Keeping good resin containment in the part after curing. • The bagging process should be done correctly to avoid the resin bleed after curing the part: • Ensuring that the vacuum bag is tightly sealed and leak free to avoid resin bleed: • A cheek sheet must be created for all parts by the quality inspector in clean room to insure the part final bagging is fully sealed. • Using leak detector to detect the vacuum level.
High Volume of Waste in bagging consumable materials	• A large amount bagging consumable materials being wasted.	• Companies can order customized bagging material consumable kit sets that can dramatically reduce the total cost of products.

Table 2. Proposed solutions for process defects

Vacuum Leak	• Vacuum hose/valve which gets damaged after 20-30 curing. • Presence of dust particles such as the carbon deposits inside the autoclave which are prone to sudden vacuum bag fail. • Incorrect positioning of vacuum valves. • Insufficient folds at corners. • Inbuilt vacuum lines blocked during layup [9].	• Ensure the vacuum hoses for leak before connecting part. • Study the tool history card and discard the tool if it is found leaking. • Ensure the absence of dust particles or FOD inside autoclave. • Ensure proper folds to avoid bridging in parts. • Ensure the vacuum valves are placed in right position over the breather/bleeder to avoid resin block in valves. • Ensure the leak rate before loading it in to autoclaves for curing process [9].
Thermocouple Failure	• Resin flash into the thermocouple that may cause electrical shorts. • The thermocouple connecting wire has been damaged, crimped or cut. • Thermocouple not properly connected at the control, e.g. the sensor connector not fully screwed-in. • Thermocouple pulls out during elevated temperatures in the autoclave due to air turbulence and tension in the thermocouple wire.	• Place flash tape below and above the thermocouple tips to protect them from resin flash and to protect the control unit from electrical shorts. • Ensure that thermocouple wire is functioning well, without any damages. • Ensure the thermocouple is fully screwed-in at the control. • Ensure proper length of thermocouples to avoid pull out due to air turbulence.
Temperature Overshot	• The controller fails to maintain the steady temperature. • The thermocouple sensor is not properly located and secured in position between the different layers.	• Check for programming/ controller errors before the start of curing. • Ensure the thermocouple is properly located and secured in the right position between the layers.

	• Placing the thermocouple under the vacuum port.	• Do not place the thermocouple under the vacuum port as the pressure may damage the lead and cause erroneous readings to occur.

6. The Impact of Implementing the Suggestions

After studying and analyzing all previous defects, and in light of cost per unit for different types of failures; it was found that if the proposed improvements have been implemented, the targeted industry will be able to save the cost of those failures. Table 3 summarizes the results of cost savings per unit cost of a failure type and number of failures per type.

Table 3. Cost saving

Summary of Cost Savings	
	$ / Month
Saving in Cost of Porosity	31,300
Saving in Cost of Delamination	38,800
Saving cost in FOD	129,000
Saving in Cost in Core Step	73,000
Saving Cost in bagging consumable materials	169,900
Saving Cost in Fixing Vacuum Bags & Thermocouple	122,500
Total ($ per Month)	564,500
Total ($ per Year)	6,774,000

7. Conclusion

In this paper the different causes for defectives in composite production has been investigated. Data have for two main groups of failures have been collected and analyzed. Use of some statistical process control tools have been utilized to sort out the causes of the different failures causes and some proposed solutions have been presented. A study of the impact of the proposed suggestions concluded that implementing the proposed solutions will have a substantial savings for company of over $6M per year. More investigation for the specific failures related to the process and implementing a reliability growth program for the processes will realize more and more savings and makes the processes more robust.

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Biography

Dr. Basel Alsayyed is an assistant professor at the department of mechanical engineering in the United Arab Emirates University. With over 16 years of experience in academia in many colleges and universities, and over 12 years of industrial experience, most of which are in the American automotive industry, Dr. Alsayyed has a passion for education in general and teaching in particular. Teaching is an art, a trust, a valuable transformation of students using certain methods and tools, and it is holy, are all part of his belief. He practices it in all aspects of his life, and to Dr. Alsayyed, students are the most valuable element in the education process; their needs have to be addressed in any continuous improvement discussion of the education process. Integration of academia and industry goals and activities are paramount. Sensing the industry needs and prepare future engineers to meet the challenges is an important dimension of Dr. Alsayyed's activities.
Dr. Alsayyed research interests are in the areas of advanced manufacturing, quality & reliability, renewable energy, engineering education and knowledge management.

Naseefa Al Ameri has received her bachelor degree in Mechanical engineering from the United Arab Emirates University, Al Ain, UAE. Currently, she is pursuing her master degree in engineering management in UAE University. She joined one of Mubadala's companies in 2013 as a Junior Manufacturing Engineer. Naseefa is a member of the American Society of Mechanical Engineers and the American Society for Quality.

Ghubaisha Al Ameri is a fresh graduate from United Arab Emirates University with a bachelor degree in chemical engineering and now she is pursuing her master degree in engineering management. Ghubaisha is an ambitious Emirati, she have a mini master of business administration diploma and she participated in international internships in Global Foundries – Singapore, Scotland – United Kingdom and South Korea. She always likes to learn something new that can add a value to herself and her country. She won the "Best of the Best Project" at the national level in the 2014 "Think Science" Competition and Fair in the category of universities and the "First Place" at the national level in the 2014 "Think Science" Competition and Fair in the category of Smart and Safety Systems.

Balqis Al Braiki has a bachelor degree in IT from UAE University with a concentration in Computer System Design. One of her professional achievements as a bachelor student is winning the second place at the national level in the 2014 "Think Science" competition and fair in the category of Smart and Safety Systems. Furthermore, she participated in Tamaiaz competition in the category of science, technology and inventions. Now, she is working as IT coordinator in UAE University. At the same time, she is doing a master degree in engineering management. Her aspiration is to be an affective person in her community. Moreover, she is looking forward to enhance her expertise in computer science and engineering management and hone other relevant skills as well.