Jordan Journal of Mechanical and Industrial Engineering (JJMIE)

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Jordan Journal of Mechanical & Industrial Engineering,
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Jordan Journal of Mechanical and Industrial Engineering

JJMIE

An International Peer-Reviewed Scientific Journal

Financed by Scientific Research Support Fund

http://jjmie.hu.edu.jo/

ISSN 1995-6665

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JJMIE
Volume 11 Number 2, April.2017
ISSN 1995-6665
Jordan Journal of Mechanical and Industrial Engineering

JJMIE

Volume 11 Number 2, April. 2017
ISSN 1995-6665
Pages 67 -71

Jordan Journal of Mechanical and Industrial Engineering

A Laboratory Automotive Suspension Test Rig: Design, Implementation and Integration

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Received Feb., 15, 2016 *Accepted Oct., 17, 2016*

Abstract

In the present paper, a laboratory test rig is designed and constructed at Hashemite University to study and analyze the effects of road terrains on automotive suspension systems. It is also used to study and analyze the nonlinear dynamic behavior of suspension systems. The proposed experimental suspension setup facilitates testing and validating various identification and controller designs. Hence, a useful educational, training, and research tool is introduced to emulate the effects of wide range of realistic road conditions on automotive suspension systems, while rapidly measuring, recording, and analyzing system variables. It should be noted that the focus of this paper is on the design and construction of a laboratory automotive suspension system test rig. Experimental testing is intended to be conducted in the future to practically demonstrate the performance of vehicular suspension under different operating modes.

Keywords: *Automotive suspension system, active and passive suspension, test rig, laboratory system*.

1. Introduction

Vehicles are typically equipped with hydraulic dampers and helical springs to isolate the car body from road irregularities and to ensure sufficient contact between tire and road. This will guarantee relatively sufficient safety and comfort for the passenger. Normally, comfort at a high level is desired which can be accomplished through reducing the vibration levels inside the car and simultaneously increasing the passenger's safety due to enhanced handling and ride stability. These performance specifications of a passenger car are mainly determined by the damping characteristic of the dampers. Passive dampers have a fixed damping characteristic determined by their design. Depending on the road excitation, however, it is desirable to adjust this characteristic to increase performance specifications. This leads to an increasing interest in active solutions. Semi-active and active suspension systems offer the possibility to vary the damper characteristics along with the road profile (e.g., by changing the restriction of one or more current controlled valves or by changing the viscosity of a magnetorheological fluid of the damper) [1]. In addition, active systems are able to supply mechanical power to each corner of the vehicle in order to dynamically adjust heave, roll and pitch motions [2, 3]. In fact, an active automotive suspension is some sort of hydraulic or pneumatic linear actuator that controls the vertical movement of the wheels relative to the chassis or vehicle body with an onboard system.

In recent years, the conception of active and semi-active suspension has been advanced, which gives a new way to improve the performance of suspension system. The adoption of active suspension system overcomes many defects of passive suspension, which can adapt the suspension system to its maximum extent under variable working conditions [4, 5]. However, there are some problems on actuator's responsive speed and fast realization of control strategy, such as structural complexity, expensive price, big volume, and heavy weight.

Active suspension system requires sensors to be located at different points of vehicle to measure the motions of the body, suspension system and/or the unsprung mass. This information is used in the vehicle controller to command the active suspension's actuator in order to provide the exact amount of force required. To meet above demands, novel vehicle passive and active suspensions were proposed and designed to allow experimental testing and analysis, such as [6, 7]. For example, the authors of [8] designed and developed a simplified and cost effective quarter car suspension test rig. They conducted an analytical analysis and experimental testing to validate the reliability of the test rig. In the last decade, many different active suspension system control approaches were developed [9–11]. The control approaches developed can be categorized into standard controllers (i.e., Proportional-Integral-Derivative (PID)) [12], linear [13], nonlinear [14], H-infinity [15], fuzzy logic [16], neural networks [17], optimal [18], and output feedback control techniques [19].

Usually, linear models are used for the design of suspension controllers. However, in order to analyze the influence of nonlinearities on the dynamic behavior, identification experiments can be conducted using a test rig to determine and identify the nonlinearities and

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uncertainties associated with the suspension components (i.e., the nonlinearities of damper and tire, as well as the relevant friction effects) [20]. These data can be used to build a precise model of the suspension system in order to develop high performance active suspension controllers and to provide a simulation platform for the controller performance before Implementing on the test rig. In addition, fault diagnostics can be performed as in [21].

The proposed test rig can be used to ultimately investigate the effects and impact of various bumps and humps in roads, on the vehicle suspension, in addition to investigate the implementation of various control and identification algorithms. Moreover, the test rig can be used to study the effect of various road bumps/humps on a traditional passive and active suspension system and perform parametric study to obtain optimum running conditions. In other words, principles of competency- and research-based learning can be experienced [22].

The remainder of the present paper is organized as follows: Section 2 describes the design of the proposed suspension system, while Section 3 introduces the system components and sizing. In Section 4, the conclusion and future work are presented.

2. System Description and Design

As stated earlier, there is a need to have a laboratory test rig to study and analyze suspension systems in automotive applications. The main objective of having such laboratory test rig at Hashemite University is to enable students, trainees, and researchers to investigate various effects and impacts of road conditions on automotive suspension system throughout analyzing different measured variables. Hence, many sensors were mounted on the proposed test rig to acquire as much information as possible about the system dynamics. In addition, computer controlled actuators were utilized to emulate the road conditions. What proposed in the present paper is a realistic test rig (i.e., real scale for actual suspension system) to acquire and analyze real data for actual vehicles. In the literature, few test rigs to investigate the performance of suspension systems were found and few researches really tested a quarter car model (e.g., [2], [6], [11], [17]). Most designs that tested suspension systems incorporated the entire vehicle.

The proposed laboratory system consists of a frame that could easily fit through standard dimensioned doors and moved about for display purposes (i.e., a base of 2.0 x 1.5m with a height of 1.8m). Criteria imposed on the test rig include reasonable compact size of design to allow for easy storage and transportation as shown in Figure 1.

The suspension system is designed to handle a maximum weight of 300kg that should be equivalent to a quarter car. Various bumps and humps can be emulated by exciting the suspension system in order to simulate forces and movements on a wheel with frequencies up to 10Hz and to simulate the vehicle running up to a speed of 162km/h (i.e., the wheel rotates at a rate of about 1250RPM given its dimensions as 205/75R15). The wheel excitation mechanism is designed to provide a maximum amplitude of 10cm at different frequencies. The proposed system is designed to emulate the actual road behavior of the suspension with the wheel rotating and vertically moving up and down. The LabVIEW developing software tool is utilized to acquire data obtained from sensors within the test rig and to control the actuators of the proposed suspension system.

The proposed test rig utilizes a servo system with a rotary AC motor coupled to a screw with a suitable pitch distance to excite the suspension system by generating a linear motion. The advantage of using a servo motor is to get a precise performance in terms of position and speed. On the other side, the angular speed of the wheel is controlled by an AC motor that is controlled by an inverter.

In addition, a 100bar hydraulic unit is installed in the test rig to operate the active suspension (two inlets/outlets hydraulic cylinder). The hydraulic unit with manually adjustable internal pressure mainly features an oil tank with its pressure relief valve, hydraulic pump, a 4/3 way directional hydraulic double valve with mid-way closed block, and two inlets/outlets hydraulic cylinder to serve as the active suspension.

A lot of sensors are inserted and mounted in different places in the proposed automotive suspension test rig to ensure capturing all possible variations in the system variables while operation. Installed sensors include two linear encoders, one rotary shaft encoder, wheel pressure sensor with display, and two accelerometers. The hydraulic unit consists of pressure, flow, and temperature sensors. Figure 2 shows a representative block diagram for the proposed suspension test rig.

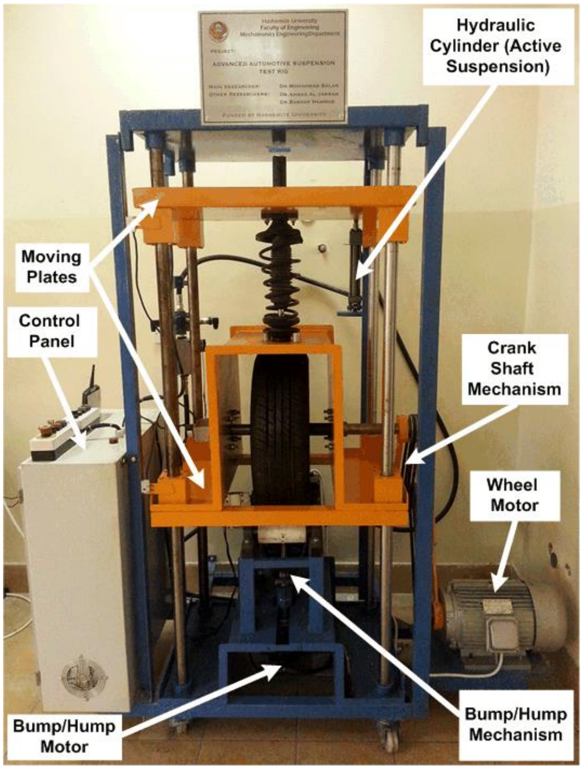


Figure 1. Automotive suspension test rig.

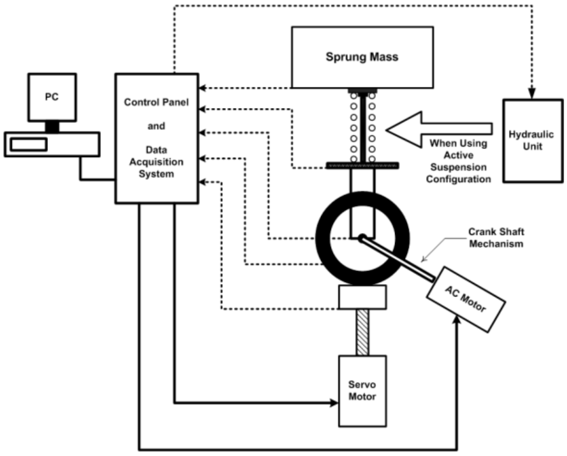


Figure 2. The automotive suspension test rig block diagram.

3. System Components and Sizing

The proposed automotive suspension system is designed and scaled to match a real quarter car so that realistic performance can be investigated and realistic data analysis can be conducted.

A. Mechanical Structure

The proposed automotive suspension test rig has two free-to-move plates; one at the top and one at the bottom as shown in Figure 1. The top plate represents quarter of the vehicle body and it carries the vehicle wheel via the suspension components (*i.e.*, spring and damper). The bottom plate is attached to the wheel to facilitate mounting and installing the suspension components. Both plates are guided by four stainless steel rods to ensure that suspension mechanism moves vertically with no torsion. The two plates are made of steel and the four bars are made of stainless steel of almost 1.8m height and diameter of 5cm, coated with chrome to make the movement of the plates easier. In addition, to enhance the easiness of plates' motion with less friction, axial bearings are mounted on the plates. A crank shaft mechanism assisted with pulleys and belts was utilized to keep the wheel rotating while moving vertically due to external emulated bumps and humps as shown in Figure 3.

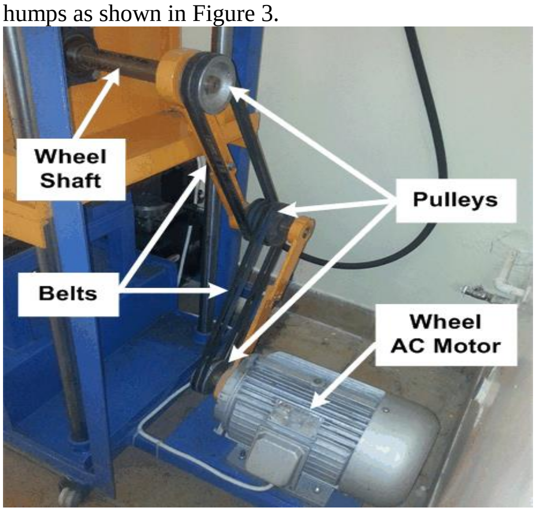


Figure 3. The crank shaft mechanism assisted with pulleys and belts to rotate the wheel while moving up and down.

In the proposed suspension test rig, the bumps and humps are emulated via an electrical rotary servo motor that is mounted at the bottom of the test rig as shown in Figure 4. The servo motor is coupled to a screw with a diameter of 10cm and 0.5cm pitch distance (i.e., one rotation provides a 5mm linear displacement per one revolution) to provide a precise linear motion. In fact, this motor excites the suspension system through the wheel by creating different shapes of bums and humps. Few examples are shown in Figure 5. The motor provides an instantaneous push (i.e., pulse) to the wheel while rotating to emulate the bump effect on the wheel (i.e., the vehicle suspension system). The motor was chosen to be servo so that it can be programmed to give a signal of constant amplitude, ramp, sinusoidal wave, or polynomial to emulate different kinds of bump actions. Servo systems are well known to provide precision in positioning and speed regulation.

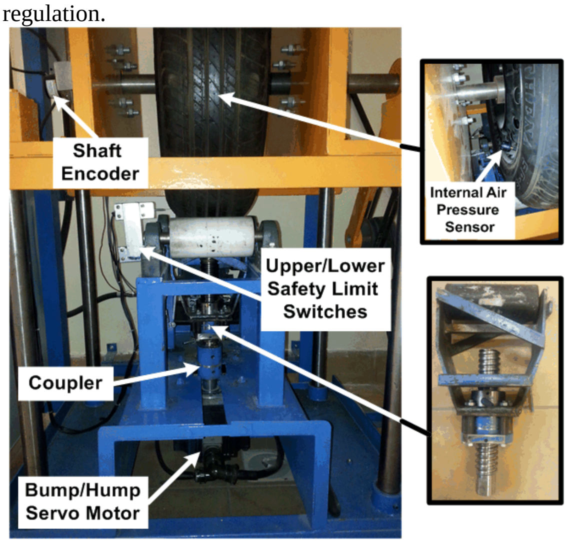


Figure 4. The motor-screw mechanism required to excite the suspension system.

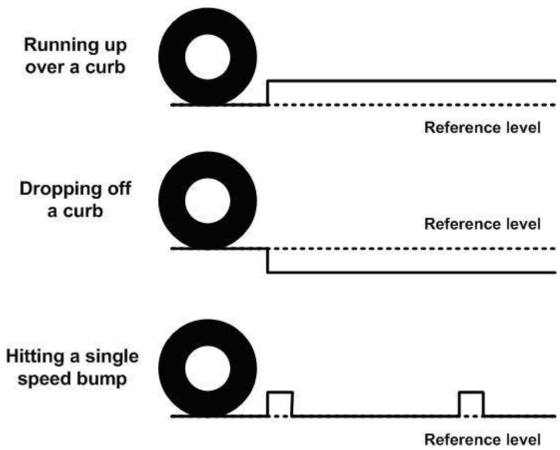


Figure 5. Examples of few bump types to excite the suspension system.

B. Actuators and Drive System

There are three actuators in the proposed test rig; two electrical and one hydraulic. One of the electrical actuators is used to rotate the wheel via the pulleys mounted in the crank shaft mechanism as shown in Figure 3. A 1.5kW three-phase induction motor is used with a rated speed of 1370RPM, rated phase voltage of 230V, and rated current of 9.64A. This AC motor was chosen to emulate the vehicle running at a maximum speed of 162km/h. An inverter is utilized in the drive system to allow changing the speed of the vehicle as desired. The second electrical motor is used to emulate the bumps and humps via a screw coupled to its shaft. A 2kW AC servo motor is used with a rated speed of 3000RPM and a rated current of 10A (e.g., LS Mecapion APM-S-C-20-A-E). The motor was chosen to handle the weight of the proposed quarter car (i.e., 300kg), suspension components, wheel, plates, and any other forces such as friction. One of the advantages of using a servo system is that it can produce a certain number of rotations to achieve a certain vertical displacement.

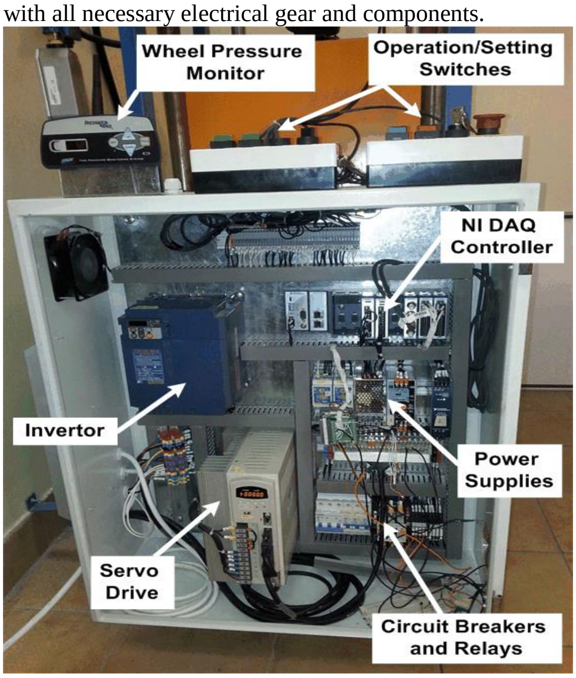
The hydraulic actuator is mainly used as an active suspension to handle the quarter car weight. In fact, either the passive suspension (i.e., spring and damper) or the active suspension (i.e., hydraulic actuator) can be used in the suspension test rig. Switching between both of them has to be done manually. More details about the hydraulic system utilized in the test rig can be found in subsection 3.E.

C. *Transducers*

Various sensors are distributed in different places in the proposed test rig. Two linear encoders (e.g., Lika SME51-L-2-10-R-2-B) and two accelerometers (e.g., PCB Piezotronics 603C01) are mounted on each moving plate to measure the linear position, speed, and acceleration. A shaft encoder (e.g., LS Mecapion S48-8-1024VL) is also mounted on the wheel shaft to measure the angular speed, hence, the vehicle speed. Two safety limit switches are mounted to prevent the bump or hump from exceeding the maximum displacement of 10 cm. A pressure sensor is mounted on the wheel, as shown in Figure 3, to provide real-time readings of the internal air of the wheel through a front monitor, as shown in Figure 6. Other sensors are used as part of the active suspension system (i.e., hydraulic unit) as presented in subsection 3.E. Note that an internal shaft encoder is embedded in the servo motor unit to provide measurements of position and speed. The torque of servo motor is measured internally by measuring active currents.

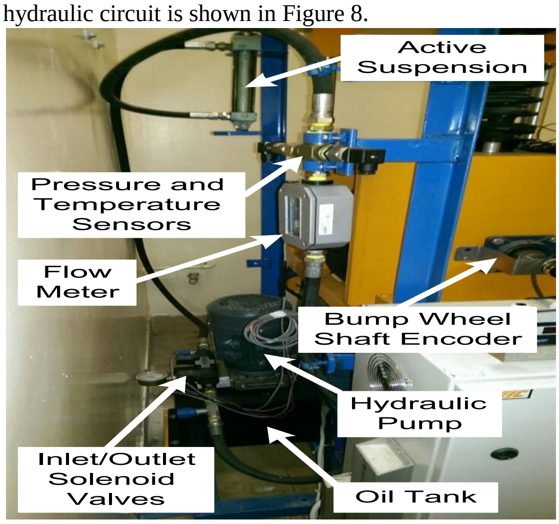
D. Main Controller

National Instruments (NI) Data Acquisition (DAQ) System (i.e., NI cRio-9074 integrated 400MHz real-time controller and 2M gate FPGA) is used as the main controller for the proposed suspension test rig. Using the LabVIEW software tool offers a great flexibility in programming as well as real-time implementation needed for any educational, training, and research purposes. Different control and measurement NI cards are used to provide variety of signals. In addition, the used NI cards are chosen to be compatible with any other electrical device used in the system, such as the drive units. The main advantage of using such interfacing system is the flexibility of changing I/O cards to suit any electrical components replaced or added to the test rig system. Figure 6 shows the control panel for the proposed test rig with all necessary electrical gear and components.



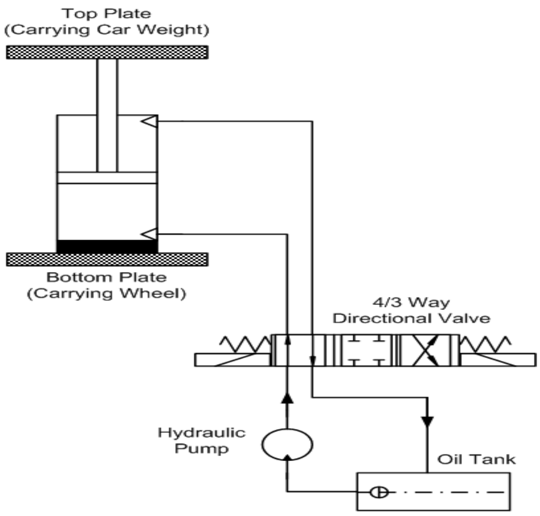
E. Hydraulic Unit

The active suspension configuration in the test rig was chosen to be a hydraulic system. Most small- and mid-sized vehicles with active suspension use hydraulic components in comparison with the pneumatic system that can be found in heavy duty vehicles such as big-size trucks. The pressure of the hydraulic unit is manually adjusted and features an oil tank with its pressure relief valve, 5hp-1500RPM hydraulic pump, a 4/3 way directional hydraulic double valve with mid way closed, and two inlets/outlets hydraulic cylinder with a piston rod of 50mm diameter, 150mm stroke, and working pressure of 150bar as shown in Figure 7. Various sensors are utilized such a flow meter (e.g., LakeMonitors LCM-505), pressure transducer (e.g., tecsis P3297), and temperature transducer (e.g., tecsis TEP11). Current-to-voltage convertors are used as well (e.g., Selet 1BS/OW) since some of the mounted sensors produce current signals. The hydraulic circuit is shown in Figure 8.



4. Conclusion and Future Work

A laboratory test rig is introduced to study the effect of road terrains on automotive suspension systems and to be used as an educational, training, and research tool. By using the proposed automotive test rig, various modeling and control techniques can be taught, designed, implemented, and tested experimentally. Eventually, the work introduced in this paper is the design, implementation, and integration of mechanical and electrical components to construct a test rig of an automotive suspension system that can be used for different purposes. In the future experimental performance testing is intended to be conducted to explore and investigate various identification and control strategies.



Acknowledgement

The present work is supported and funded by Hashemite University, Jordan, under grant no HU/12/12/2010.

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JJMIE

Volume 11 Number 2, April. 2017
ISSN 1995-6665
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Pinning Effect of Pores on Grain Growth in Sintered Steel

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Received Jan., 25, 2017 *Accepted Oct., 13, 2017*

Abstract

The effect of pore drag on grain growth is one of the most frequent effects encountered in the last stage of sintering. Therefore, the understanding of the effect of microstructure and pore location, pore morphology on grain growth is essential. Here a migrating grain boundary interacts with pores and other grain boundaries such that its structure and energy vary during grain growth. Consequently, it is of great interest to see whether the grain boundary energy decreases or increases during the interaction between migrating grain boundaries and pores. In this paper, the conditions for grain boundary migration and pinning are related to pore curvature and illustrated theoretically and experimentally.

Keywords: *pore rounding, pore drag, grain growth, grain boundaries*.

1. Introduction

The mechanical properties of P/M materials are directly related to their microstructure and to the porosity, pores dimension, distribution, and morphology. Densification by pore elimination and grain coarsening occur simultaneously during sintering [1,2]. In the intermediate stage of sintering, pores shrink and in the last stage, grains grow to reduce the total surface and grain boundary energy [3]. Here grain boundaries with pores are a result of the misfit between particles. These pores may either retard grain growth, be separated from the grain boundaries, or move along with the grain boundaries [4]. Pores at grain boundaries, as well as triple junctions, act as pinning points that exert Zener drag on the moving grain boundaries, hence lowering the grain growth rate or leading to grain growth stagnation [4, 5, 6].

In essence, pores on the grain boundaries prevent their migration and inhibit grain growth up to a sinter density of 90 pct of the theoretical density [7]. Thereafter, the number of pores decreases and cannot hinder grain boundary migration causing rapid grain growth.

In sintering, pores shrink and change their shape by rounding off their sharp edges and develop facets as vacancies diffuse away from the pores to sinks like grain boundaries. The morphology of pores at grain boundaries are characterized by a lenticular shape, and pores within the grains are characterized by a spherical shape [8]. This occurs during the intermediate stage of sintering where the pores become smoother [9].

The presence of different curvatures inside a single pore activates the diffusion of vacancies. Therefore, smoothening off the irregularities in the same pore. So, the rounding of pores is controlled by the diffusion of vacancies [10, 11]. The vacancies concentration gradient set up by local variation of curvature activates the diffusion of vacancies [12]. Accordingly, where the surface is convexly curved, a lower vacancy concentration is found compared to concavely curved parts of the surface [8].

Most sintering models assume that accelerated grain growth occurs during the final stage of sintering and that the pore drag effect retards grain growth as long as the pores are attached to the boundary. From these models, the mechanisms controlling grain growth by pores are explained by four behaviours.

Firstly, reduced pore mobility *Mp* where pore drag controls grain growth. This is done by reducing either the diffusion coefficients of surface diffusion *Ds* and the vapor phase diffusion coefficient *Dv*, or the diffusion coefficient of lattice diffusion D_L [13]. The mobility of pores during the last stage of sintering is lower than the mobility of grains [14, 15]. If grain boundary migration is fast, pores detach from the grain boundaries. Once free from the pores the grain boundaries grow faster and consequently the pore detachment leads to a porous, *i.e.* coarse grained material [16].

Secondly, the drag effect of the pores which are quantified by considering a force balance at the pore surface. Provided that the free surface energies are isotropic, the theoretical shape of pores located at symmetric three-grains junctions is dependent on the dihedral angle as seen from Fig. 1.

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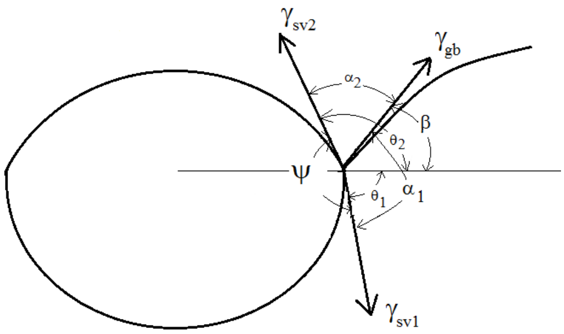

Figure1. Schematic illustration of dihedral angle ψ for solid-pore interaction adapted from [17, 18, 19, 20].

High dihedral angles mean that the grain boundary energy is low and that these grains are more likely to abnormally grow [17, 18, 21]. An increase in the dihedral angle produces an increase in the grain boundary area. The balance of force at the intersection point of the grain boundary and the pore is governed by the equation:

$$\gamma_{gb}\cos\beta = \gamma_{sv}\cos\theta_1 + \gamma_{sv}\cos\theta_2 \qquad (1)$$

Though these models provide insight on pore drag and pore grain separation, the main common assumption made in these models is that: 1- the pores are of spherical morphology; 2- the angles between the surface tensions for both the trailing and the advanced parts of the pore and the grain boundary energy are equal $\alpha_1=\alpha_2$. This leads to a simplified formula for the drag force the pore exerts on the grain boundary as follows:

$$F = 2\pi r\gamma_{sv}\cos\beta\cos(\alpha-\beta) \qquad (2)$$

Thirdly, the surface tension for both the trailing and the advanced part of the pore are equal. Lastly, there have been no attempts to incorporate the torque term in the force balance at the intersection point.

The primary aim of this work is to prove that detachment of pores from grain boundaries is only possible when the pore's two parts, the trailing and the advanced part, have the same radius of curvature. This work will give an attempt by using Gibbsian interfacial thermodynamics and experimental results to prove that grain boundary detachment from pores is only possible with pore spherodizing, which results from pore rounding due to surface diffusion. Thermodynamics of interfaces will be used without ignoring the effects of surface curvature.

2. Materials

The iron base powders used in experiments were ASC100 and ASC300 provided by Höganäs AB. Their maximum particle sizes are 150 µm and 45 µm, respectively, with an apparent density 3.0 g/cm^3. Three types of liquid forming additives from Höganäs AB were added to these base powders to generate a liquid phase at sintering temperature. They are pre-alloyed Fe-P-C, Fe-P-C-Mn and Fe-P-C-Cu powders produced by water atomisation. These liquid forming additives are named *LP1*, *LP2*, and *LP3* and they have P/C weight fraction ratios of 7.5, 9.33 and 8.88, respectively. Varying amounts of the liquid forming additives were mixed with the base powders to yield different fractions of liquid phases at the sintering temperature. To study the pore structure after sintering, three samples were prepared from mixing three different additives in various amounts to the base powders in order to achieve the highest possible sintered density. The compositions of the additives are shown in Table 1.

Table 1. Composition of the three samples

Samples	% C	% P	% Mn	% Cu
1	0.32	2.44	0	0
2	1.35	1.35	0	1.3
3	0.47	0.27	0	0.26

Sintering was done in N2 at 1120 °C or 1150 °C for two hours. Experiments were performed with two different heating rates of 5 and 20 °C/min.

Sample1 is made of a 30g powder mixture having a cylindrical cross section of 20mm diameter. The sample was sintered at 1120°C for two hours. This sample had a sinter density of around 98% and was subjected to long annealing at 1000 °C for 24 hours to develop the dihedral angles between pores and grain boundaries. At least 200 dihedral angles were measured for each material to obtain a statistical distribution. The heat treatment was carried out for 24 hours at 1000 °C. The atmosphere was pure N2 and the samples were cooled in air. If the *Tm* is taken as the melting temperature of pure Fe then the holding temperature for the heat treatment at 1000 °C is in the high temperature range > 0.5*Tm*. This was done to promote solid phase sintering and to dissolve the Fe_3P.

Sample 2 was double sintered first at 970 °C followed by decarburization then heated up to 1350 °C for 5 minutes. Decarburisation heat treatment was carried out in a tube furnace sealed from both ends with a reducing wet gas mixture (90%N2–10%H2). The moisture content of the atmosphere was increased by letting this gas mixture through a water container at room temperature prior to entering the furnace.

Sample3 had a rectangular cross-section of 6x6 mm^2 and was produced with different chemical compositions from powder blends of iron base powder 80% (ASC300), water-atomised liquid forming master alloy powder 10% (2.7wt% P, 2.7wt% C and 2.6wt% Cu), 0.2% graphite and lubricant addition of 0.8 wt-% H-wax. The sample was manufactured by means of single stage die compaction at 500 MPa. The green density of the die pressed sample is 83 %. After sintering, the sample was decarburised in a tube furnace starting with a gas mixture of 10% H2 and 90% N2 during heating of the sample. Then, at a temperature of 1100 °C, the moisture content of the atmosphere was increased by letting this gas mixture through a water container at room temperature prior to the furnace while heating continued at the rate of 5 °C/min to 1200 ºC with a final holding time of 120 minutes.

3. Results

Fig.2a and Fig.2b show the resulting fracture surfaces of sample 1 after being heat treated. Irregular and spherical pores at the grain boundaries are observed and no internal pores were present.

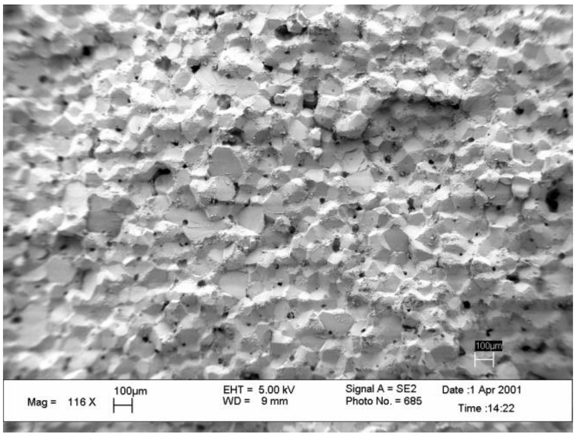

Figure 2a. Fracture surface of a Sample1 after being heat treated showing areas of porosity as well as a brittle fracture mode. The grain boundaries have no curvature.

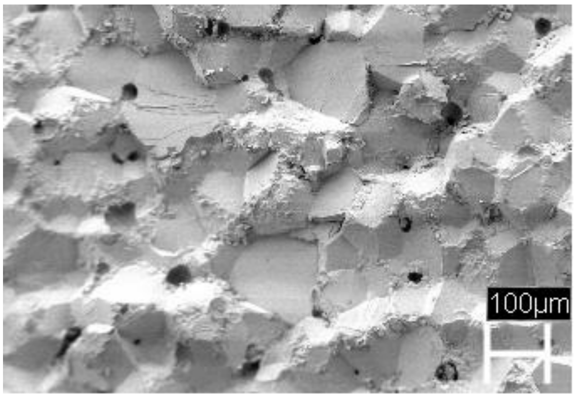

Figure 2b. Fracture surface of a Sample1 after being heat treated showing areas of porosity as well as brittle fracture mode.

Fig.3 shows the microstructure of Sample2 after final stage sintering at 1350°C for 5 minutes showing a ferritic structure surrounded by rounded pores at boundaries and the interior. Sample2 was decarburized at around 970°C for complete removal of carbon.

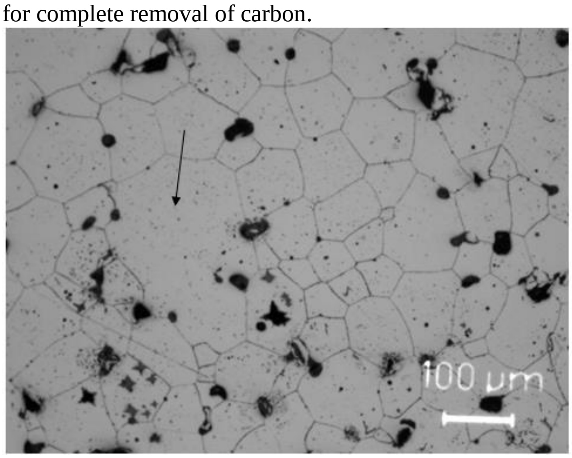

Figure 3. Microstructure of Sample2 after final stage sintering at 1350°C for 5 minutes showing ferritic structure surrounded by pores. Depicting a large, 14-sided grain.

The micrographs of Fig.1 and Fig.2 clearly show a good degree of sintering in terms of pore rounding and sinter bonding of the iron particles. Fig.3 shows the microstructure of Sample3 after decarburization. The pore morphology is not rounded as in Sample1 and Sample2. Rather, the pores' morphologies are equiaxed and the segment of the grain boundaries at the intersection points with the pores are straight. The pores are mainly concentrated at grain-particle boundaries having an irregular crack like morphology.

The morphology of pores follows wedge-type cracks interconnected to each other at grain boundaries. Here, interconnected porosity with small particle necks dominate. The observations made from the pinned grain boundaries by pores are as follows:

1. The segment of the grain boundary closest to the pore is straight having no curvature.
2. The point where the grain boundary is pinned at the pore's surface is between two different curvatures.
3. The segment of the grain boundary that is not pinned is curved.

4. Discussion

By deploying Gibbsian interfacial thermodynamics without ignoring effects of surface curvature, and through experimental results, we hope to demonstrate that grain boundary detachment from pores is only possible with pore spherodizing, which results from pore rounding owing to surface diffusion.

The micrographs seen in Fig.2 to Fig.4 clearly indicate that the alloying, heat treatment, time and temperature have a significant influence on the sintering response of the material and the morphology of the pores in the sintered material.

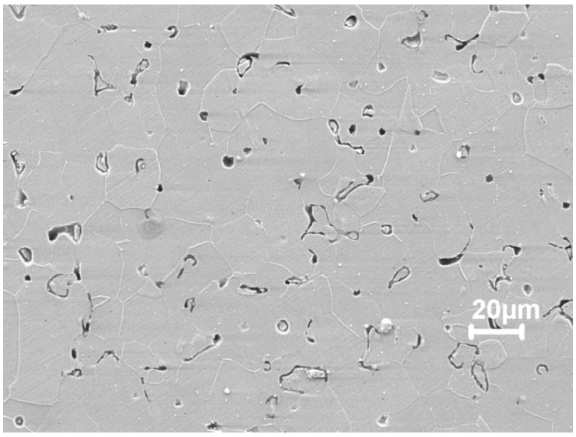

Figure 4. Optical micrograph of Sample3 decarburized at 960 C. Irregular crack-like lines at the grain boundaries and some spherical pores, as well as a spherical internal porosity are observed.

The porosity seen here is typical of most ferrous P/M materials. The analysis of the evolution of the microstructures through the use of heat treatment of Sample1 can be utilized to explain the effect of P content on the morphology of pores as reported earlier [19]. Heat treatment of the low C content in Sample1 resulted in increased pore refinement. Heat treatment resulted in higher, almost complete, dissolution of Fe_3P. This provides a higher P content at the grain boundaries which resulted in pore rounding.

Heat treatment promotes neck growth and solid phase sintering leading to change in pore morphology. Fig.1 shows how pores are more rounded. It can be seen from Fig.1 through Fig.4 how pores are located at grain boundaries and increase in size relatively. Looking at the micrographs, one can find many examples of bent boundaries in cases where equilibrium is not attained, and planar or straight grain boundaries when equilibrium is attained. When the pore's two parts, the trailing and the advanced part, have two different radii of curvature the slope of the two parts at the point of intersection with the grain boundary will be different as seen in Fig.5. The grain boundary is also a straight line.

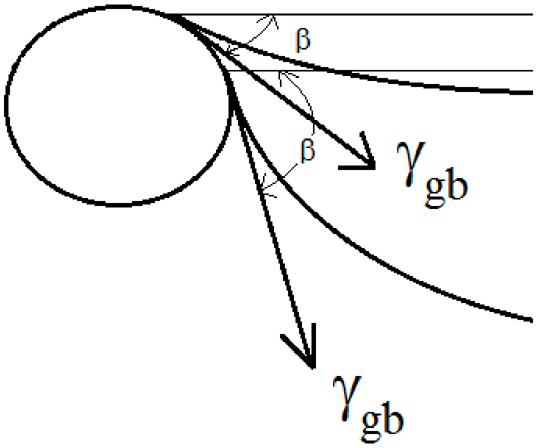

Figure 5. Schematic representation of a migrating grain boundary showing geometrically, a decreasing β value.

At equilibrium with no grain migration, there should be a balance of forces at the junction between the pore surface and the grain boundary. This is governed by the equation:

$$\gamma_{gb}\cos\beta = \gamma_{sv2}\cos\theta_2 - \gamma_{sv1}\cos\theta_1 \tag{3}$$

, while taking the total derivative of γ_{gb} to be:

$$d\gamma_{gb} = \frac{\partial\gamma_{gb}}{\partial\gamma_{sv1}}d\gamma_{sv1} + \frac{\partial\gamma_{gb}}{\partial\gamma_{sv2}}d\gamma_{sv2} + \frac{\partial\gamma_{gb}}{\partial\theta_1}d\theta_1 + \frac{\partial\gamma_{gb}}{\partial\theta_2}d\theta_2 + \frac{\partial\gamma_{gb}}{\partial\beta}d\beta \tag{4}$$

, and the total derivative $d\gamma_{gb}$ as:

$$d\gamma_{gb} = -\frac{\cos\theta_1}{\cos\beta}d\gamma_{sv1} + \gamma_{sv1}\frac{\sin\theta_1}{\cos\beta}d\theta_1 + \frac{\cos\theta_2}{\cos\beta}d\gamma_{sv2} - \gamma_{sv2}\frac{\sin\theta_2}{\cos\beta}d\theta_2 + \gamma_{gb}\tan\beta d\beta \tag{5}$$

Knowing that the curvature k is the derivative of the tangent angle θ with respect to the arc length [22], the curvature at that point is:

$$\frac{d\theta}{ds} = \frac{dT}{ds} = k \quad \text{and} \quad \frac{d\beta}{ds_{gb}} = k_{gb} \tag{6}$$

Using the definition of the curvature in eq.(5) and dividing by ds we obtain:

$$\frac{d\gamma_{gb}}{ds} = -\frac{\cos\theta_1}{\cos\beta}\frac{d\gamma_{sv1}}{ds} + \frac{\cos\theta_2}{\cos\beta}\frac{d\gamma_{sv2}}{ds} + \gamma_{sv1}\frac{\sin\theta_1}{\cos\beta}k_1 - \gamma_{sv2}\frac{\sin\theta_2}{\cos\beta}k_2 + \gamma_{gb}\tan\beta k_{gb}\frac{ds_{gb}}{ds} \tag{7}$$

The presence of the derivative of the grain boundary energy and the free surface indicates that both the boundary energy and the surface energy vary with the normal of the pore and the normal to the grain boundary at the point of intersection. This is a torque term per unit area of the pore. The tangential component of this equation acts to minimize the surface area, while the normal component rotates the interface towards an orientation with a lower interfacial area.

At minimum energy, the surface tension of the intersection must be in mechanical equilibrium, satisfying the following Herring torque relation [23]:

$$\sum_{i=1}^{3}\left(\gamma_i\hat{t}_i + \frac{\partial\gamma_i}{\partial t_i}\hat{n}_i\right) = 0 \tag{8}$$

The summation of the torque terms should be zero to satisfy mechanical equilibrium. The junction between a pore and two grains is considered to be a poly-phase junction. Thus, the angle between two inter-phase boundaries is the dihedral angle. By examining the micrographs, in particular the junctions between pores and grain boundaries, it is evident that the two grain-pore junctions do not meet at 120˚. This confirms that the interfacial energy and the grain boundary energy is not constant with the orientation of the interface and the grain boundary. This means that the normal term in eq.(8) should be considered. The angle varies according to the relative orientation of the grains at the junction.

When the specific surface free energy is isotropic, the resulting pore surface defines a sphere. Thus leading to the conclusion that $\gamma 1=\gamma 2$ and $d\gamma=0$. This means that here, there is no need for a grain boundary between the two points.

For the present discussion we may consider that only the energy of the pore surface remains unchanged during the growth of the grain. Thus, forcing $\gamma_{sv1}=\gamma_{sv2}$ and $\theta_1+\theta_2=180$ leading to $\sin\theta_1=\sin\theta_2$ and $\cos\theta_1=-\cos\theta_2$. In addition, from the experimental observation of the pore's equal curvature at the point of conjunction, at the trailing and advanced parts, we set $k_1=k_2$. Substituting these conditions into eq.(5) yields:

$$\frac{d\gamma_{gb}}{ds} = +\gamma_{gb}\tan\beta k_{gb}\frac{ds_{gb}}{ds} \tag{9}$$

,and using the definition of the curvature again, we find:

$$\frac{d\gamma_{gb}}{ds} = \gamma_{gb} \tan\beta \frac{d\beta}{ds} \quad (10)$$

This additional force on the grain boundary can be interpreted physically as producing a torque on the moving grain boundary that changes the moving grain boundary direction so as to follow the periphery of the pore surface. The force that produces this torque must act perpendicularly to the grain boundary's propagation direction. The Herring torque is produced by a physical force associated with the grain boundary energy γ_{gb}, which is generally anisotropic. This force acts perpendicularly to each grain boundary segment at the junction of the grain boundaries and pores.

Pore-drag reduces the grain boundary mobility by applying a pinning pressure on grain boundaries. In order for grain growth to be inhibited, the grain boundaries must become immobile requiring the drag pressure to be larger than the driving pressure, hence:

$$P_{drag} > P_{growth} \quad (11)$$

From all the experimental observations of pores, the grain boundary is always pinned where there is a difference in curvature between the trailing part and the advanced part of the pore at the point of conjunction. Each point of the grain boundary curve migrates in the direction of the normal vector to the curve. The driving force acting on the grain boundary is due to the grain boundary curvature, Here, the change in grain boundary energy is $\gamma K\, dK$ and the pressure on a boundary is given by the Young–Laplace equation [24]:

$$P_{gb} = \gamma_{gb} k_{gb} \quad (12)$$

, where k_{gb} is the average curvature of the grain boundary. The only fronts of the grain boundary that do not move are straight line segments with $k_{gb}=0$. Also, the total derivative of the pressure acting on the grain boundary is defined as:

$$dP_{gb} = \gamma_{gb} dk_{gb} + k_{gb} d\gamma_{gb} \quad (13)$$

Dividing by ds and using eq.(10) yields:

$$\frac{dP_{gb}}{ds} = \gamma_{gb} \frac{dk_{gb}}{ds} + \gamma_{gb} \tan\beta \frac{d\beta}{ds} \quad (14)$$

Moving along the pore surface by ds from the trailing to the advance part of the pore, the pressure will be:

$$P_{gb} + \frac{dP}{ds} ds = \gamma_{gb} k_{gb} + \gamma_{gb} \tan\beta \frac{d\beta}{ds} \quad (15)$$

By examining Fig.5 one can see that geometrically $d\beta/ds \le 0$ thus the second term on the right will decrease the pressure. Mathematically, the tangent on both sides of the grain boundary at the point of intersection is the same. This means that the first derivative does not change when crossing the point of intersection from the trailing to the advance part of the pore, which causes the pressure to decrease.

In contrast, if the slope is not the same at the point of intersection where the slope is discontinuous, is called a "cusp". Here, the grain boundary's curvature will become zero and the migrating pressure at the intersection point becomes zero. The pinning point on the pore's surface will acquire a zero pressure on the grain boundary. This point will have a zero curvature. It is a point where the curvature vanishes but does not change sign in mathematical terms. This is called an undulation point.

As illustrated by Fig.6 the intersection points are like a corners or cusps. Thus, they are local extrema points and the points of intersection are critical points. Such a critical point is the end point of the trailing part of the pore at which dk_{gb}/ds and $d\gamma_{gb}/ds$ do not exist. Thus, there will be a jump in the pressure across from the trailing part to the advance part. The intersection point jumps from the trailing part to the advance part and this jump makes the function discontinuous and pins the grain boundary.

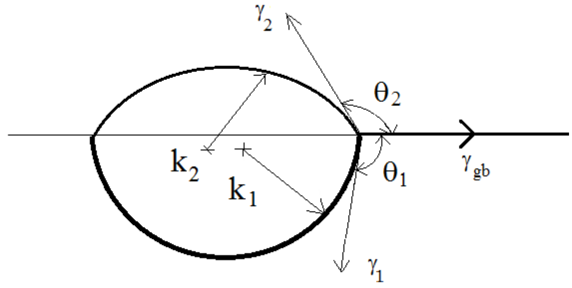

Figure 6. A schematic showing a pinned grain boundary by a pore. Here β=0.

The velocity of the Grain boundary of a growing grain is related to the driving pressure of grain growth. As described by Rollett *et al.* [25], as well as by Gottstein and Shvindlerman [26], the grain boundary velocity and pressure during primary recrystallization can be represented as:

$$v_b = M_b P \quad (16)$$

The point of intersection moving along the periphery of the pore according to eq.(14) will have a lower pressure compared to the rest of the grain boundary points. This means that the velocity of the intersection point is slower than the rest of the grain boundary. When the intersection point reaches a point on the periphery of the pore's surface having a discontinuity in β or a sudden change in curvature, it will acquire a zero velocity according to eq.(16) thus the rest of the grain boundary will catch up with the intersection point and it will plan out.

From all the observations made on pores at the points of conjunction, it can be concluded that where the grain boundary is pinned its intersection point is straight. In this work, we propose that by considering the 2-D cross section seen in Fig.7 the point of intersection between the grain boundary and the pore will migrate on the pore's periphery ahead of the rest of the grain boundary so as to keep the curvature of the migrating grain boundary convexly curved. Local equilibrium is governed by the balance between the free energy to bow the grain boundary and the free energy to bend the angle of intersection of the grain boundary. Once the intersection point reach a stage where there are two different curvature values, the intersection point will stagnate and the rest of the grain boundary will follow.

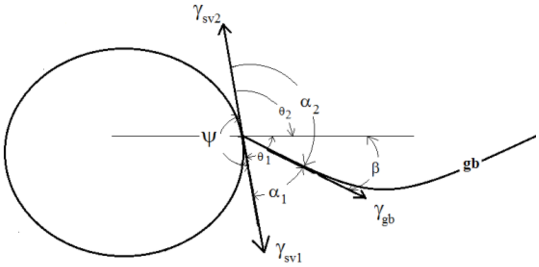

Figure7. Schematic illustration of an unpinned grain boundary for a solid-pore.

5. Conclusions

The pore surface consists of circular arcs in two dimensions and spherical caps in three dimensions. The grain boundary migrates as long as the curvature of the circular segment is constant; however, as the migrating grain boundary meets a junction of two arcs with different curvatures, or a junction of one arc and a straight segment, or a junction of two linear segments, it will be pinned at the pore surface and the grain boundary will attain a zero curvature. The morphology of pinned pores on grain boundaries is characterized by a lenticular shape with different curvatures at the intersection point from the trailing part and from the advanced part.

Consequently, detachment from pores is only possible with pore spherodizing, which results from pore rounding due to surface diffusion.

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JJMIE

Volume 11 Number 2, April. 2017
ISSN 1995-6665
Pages 79 -95

Jordan Journal of Mechanical and Industrial Engineering

Buckling Analysis of Nonlocal Embedded Shear Deformable Functionally Graded Piezoelectric Nanoscale Beams

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Received Mar., 27, 2016 *Accepted Feb., 10, 2017*

Abstract

Buckling behavior of nonlocal Functionally Graded Piezoelectric (FGP) beams on elastic substrate via a higher order beam model is examined. The present beam model takes into consideration the shear deformation effects needless of any shear correction factor. Employing power-law function, the gradation of material properties of the beam is described. Incorporation of small scale parameter is carried out using nonlocal elasticity theory. Implementing an analytical approach which satisfies simply-supported boundary conditions, the governing equations derived from Hamilton's principle are solved. The obtained results are compared with those provided in the literature. It is indicated that the buckling behavior of piezoelectric Nanobeams is significantly influenced by elastic foundation parameters, external voltage, scale parameter, power-law index and slenderness ratio.

Keywords: *Functionally graded piezoelectric nanobeam; Elastic foundation; Buckling; Nonlocal elasticity theory; Third-order beam theory.*

1. Introduction

Functionally Graded Materials (FGMs) are well known as an alternative materials, which are extensively applied in chemical, mechanical, electronic, civil, automotive and optical industries due to possessing supreme mechanical performance compared to classical composite materials. FGMs have microscopically heterogeneous structure, and material properties change with continuous composition gradation from one surface to another [1-9]. Nowadays, functionally graded materials have been extensively utilized in micro-electromechanical and nano-electromechanical systems and devices. On the other hand, microstructures, such as micro and nano scale beams are key components in many structures so that of mechanical behavior analysis of micro/nano beams received striking attention from research communities [10]. The classical continuum theory can properly applied in the mechanical analysis of the macroscopic structures, but it is unable to consider the size effect on the mechanical behaviors on micro/nano structures. While, due to the classical continuum theory is scale-independent, it needs to incorporate a higher-order continuum theory to capture size effects.

Thus, this can be attained by the nonlocal elasticity theory proposed by Eringen [11-13] in which a stress state at a reference point is suggested as a function of the strain of all neighbor points. It is noted that some studies are published on mechanical behavior of size-dependent FG beams. As one the first attempt to study this case, Simsek and Yurtcu [14] investigated bending and buckling behavior of size-dependent FG nanobeam using analytical method and Timoshenko and Euler-Bernoulli beam models. Also, the static and stability behavior of FG nanobeams based on nonlocal continuum theory is studied by Eltaher *et al.* [15]. Nonlinear free vibration of functionally graded nanobeams within the framework of Euler–Bernoulli beam model including the von Kármán geometric nonlinearity studied by Sharabiani and Yazdi [16]. Also, forced vibration analysis of Functionally Graded (FG) nanobeams based on the nonlocal elasticity theory and using Navier method for various shear deformation theories studied by Uymaz [17]. Zemri *et al.* [18] investigated the size effects on vibration of nanobeams based on nonlocal refined beam model. Nonlinear free vibration of FG nanobeams with fixed ends, i.e., simply supported-simply supported (SS) and simply Supported-Clamped (SC), using the nonlocal elasticity within the frame work of EBT with von kármán type nonlinearity is studied by Nazemnezhad and Hosseini-Hashemi [19]. Also, Ebrahimi et al. [20, 21] examined the applicability of differential transformation method in investigations on vibrational characteristics of FG size-dependent nanobeams. In another work, Ebrahimi and Salari [22] presented a semi-analytical method for vibrational and buckling analysis of FG nanobeams considering the position of neutral axis. An exact solution for the nonlinear forced vibration of functionally graded nanobeams in thermal environment based on surface elasticity theory is presented by Ansari *et al.* [23]. Recently, Rahmani and Jandaghian [24] presented Buckling analysis of functionally graded nanobeams based on a nonlocal third-order shear deformation theory. Also, vibration behavior of functionally graded nanoscale plates using a zeroth-order theory is examined by Bounouara *et al.* [25]. Vibration of Axially Functionally Graded

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Material (AFGM) nanobeam is investigated by Zeighampour and Beni [26] using strain gradient theory.

Piezoelectric materials are certain class of solid materials which convert mechanical load to electrical energy and vice versa. Such materials are applied in a wide range of systems and devices, such as sensors, actuators, speakers and timing devices. So, the application of piezoelectric materials for the vibration diminution and shape control is a useful tool in smart devices and systems design [27]. Mechanical responses of a FGP cantilever beam under loads are investigated by Shi and Chen [28]. Doroushi *et al*. [29] investigated the free and forced vibration characteristics of an FGPM beam subjected to thermo-electro-mechanical loads using the higher-order shear deformation beam theory. Kiani, Y. *et al*. [30] analyzed buckling behavior of functionally graded material (FGM) beams with or without surface-bonded piezoelectric layers subjected to both thermal loading and constant voltage. Komijani *et al*. [31] studied free vibration of Functionally Graded Piezoelectric Material (FGPM) beams with rectangular cross sections under in-plane thermal and electrical excitations in pre/post-buckling regimes. Lezgy-Nazargah *et al*. [32] suggested an efficient three-nodded beam element model for static, free vibration and dynamic response of functionally graded piezoelectric material beams. Large amplitude free flexural vibration of shear deformable Functionally Graded Materials (FGMs) beams with surface-bonded piezoelectric layers subjected to thermo-piezoelectric loadings with random material properties presented by Shegokar and Lal [33]. Therefore it could be noted that the most important imperfection of above researches is that the small size effects is not considered in these studies. A few studies are conducted to analyze mechanical behavior of size-dependent FGP beams. Among them, vibration behavior of piezoelectric microbeams is studied by Ansari *et al*. [34] on the basis of the modified couple stress theory. Also, Sahmani and Bahrami [35] investigated size-dependent dynamic stability analysis of microbeams actuated by piezoelectric voltage based on strain gradient theory.

Electro-mechanical buckling problem of functionally graded piezoelectric nanobeams supported by Winkler–Pasternak elastic foundation subjected to electric voltage is analyzed via the higher order beam model. The electro-mechanical material properties of the beam are supposed to be graded in the thickness direction according to the power law distribution. The small size effect is captured using Eringen's nonlocal elasticity theory. Coupled governing equations for the buckling of embedded FGP nanobeams have been derived via Hamilton's principle and they are solved using Navier type method. Finally, several numerical results are provided investigating the influences of elastic foundation, external electric voltage, nonlocal parameter, power-law index and slenderness ratio on buckling behavior of embedded FGP nanobeams.

2. Theoretical Formulations

2.1. The Material Properties of FGP Nanobeams

Assume a functionally graded nanobeam composed of PZT-4 and PZT-5H piezoelectric materials exposed to an electric potential $\Phi(x,z,t)$, with length L and uniform thickness h, as shown in Figure 1. The effective material properties of the FGPM nanobeam are supposed to change continuously in the *z*-axis direction (thickness direction) based on the power-law model. So, the effective material properties, *P*, can be stated in the following form [1]:

$$P = P_2 V_2 + P_1 V_1 \tag{1}$$

In which P_1 and P_2 denote the material properties of the bottom and higher surfaces, respectively. Also V_1 and V_2 are the corresponding volume fractions related by:

$$V_2 = \left(\frac{z}{h} + \frac{1}{2}\right)^p, \quad V_1 = 1 - V_2 \tag{2}$$

Therefore, according to Eqs. (1) and (2), the effective electro-mechanical material properties of the FGP beam is defined as:

$$P(z) = \left(P_2 - P_1\right)\left(\frac{z}{h} + \frac{1}{2}\right)^p + P_1 \tag{3}$$

where p is power-law exponent which is t non-negative and estimates the material distribution through the thickness of the nanobeam and *z* is the distance from the mid-plane of the graded piezoelectric beam. It must be noted that, the top surface at $z = +h/2$ of FGP nanobeam is assumed PZT-4 rich, whereas the bottom surface ($z = -h/2$) is PZT-5H rich.

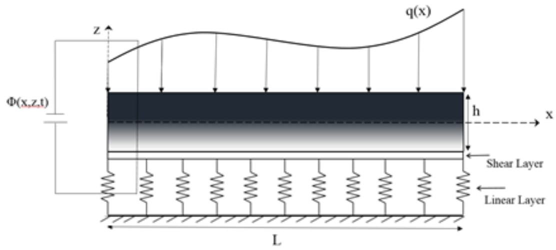


Figure1. Configuration of an embedded functionally graded piezoelectric nanobeam.

2.2. Nonlocal Elasticity Theory for the Piezoelectric Materials

Contrary to the constitutive equation of classical elasticity theory, Eringen's nonlocal theory notes that the stress state at a point inside a body is regarded to be function of strains of all points in the neighbor regions. For a nonlocal homogeneous piezoelectric solid the basic equations with zero body force may be defined as:

$$\sigma_{ij} = \int_V \alpha\left(\left|x' - x\right|, \tau\right)\left[C_{ijkl}\varepsilon_{kl}(x') - e_{kij}E_k(x')\right]dV(x') \tag{4a}$$

$$D_i = \int_V \alpha\left(\left|x' - x\right|, \tau\right)\left[e_{ikl}\varepsilon_{kl}(x') + k_{ik}E_k(x')\right]dV(x') \tag{4b}$$

where σ_{ij}, ε_{ij}, D_i and E_i denote the stress, strain, electric displacement and electric field components, respectively; C_{ijkl}, e_{kij} and k_{ik} are elastic, piezoelectric and dielectric constant, respectively; $\alpha\left(\left|x' - x\right|, \tau\right)$ is the nonlocal kernel function and $\left|x' - x\right|$ is the Euclidean distance. $\tau = e_0 a / l$ is defined as scale coefficient, where e_0 is a material constant which is determined experimentally or approximated by matching the dispersion curves of plane waves with those of atomic lattice dynamics; and *a* and *l* are the internal and external characteristic length of the nanostructures, respectively. Finally it is possible to represent the integral constitutive relations given by Eq. (4) in an equivalent differential form as:

$$\sigma_{ij} - (e_0\, a)^2 \nabla^2 \sigma_{ij} = C_{ijkl}\varepsilon_{kl} - e_{kij}E_k \tag{5a}$$

$$D_i - (e_0\, a)^2 \nabla^2 D_i = e_{ikl}\varepsilon_{kl} + k_{ik}E_k \tag{5b}$$

where ∇^2 is the Laplacian operator and $e_0 a$ is the nonlocal parameter revealing the size influence on the response of nanostructures.

2.3. Nonlocal FG Piezoelectric Nanobeam Model

Based on parabolic third order beam theory, the displacement field at any point of the beam is supposed to be in the form:

$$u_x(x,z) = u(x) + z\psi(x) - \alpha z^3(\psi + \frac{\partial w}{\partial x}) \tag{6a}$$

$$u_z(x,z) = w(x) \tag{6b}$$

in which u and w are displacement components in the mid-plane along the coordinates x and z, respectively, while ψ denotes the total bending rotation of the cross-section.

To satisfy Maxwell's equation in the quasi-static approximation, the distribution of electric potential along the thickness direction is supposed to change as a combination of a cosine and linear variation as follows:

$$\Phi(x,z,t) = -\cos(\xi z)\phi(x,t) + \frac{2z}{h}V \tag{7}$$

where $\xi = \pi / h$. Also, V is the initial external electric voltage applied to the FGP nanobeam; and $\phi(x,t)$ is the spatial function of the electric potential in the *x*-direction. Considering strain–displacement relationships on the basis of parabolic beam theory, the non-zero strains can be stated as:

$$\varepsilon_{xx} = \varepsilon_{xx}^{(0)} + z\varepsilon_{xx}^{(1)} + z^3\varepsilon_{xx}^{(3)} \tag{8}$$

$$\gamma_{xz} = \gamma_{xz}^{(0)} + z^2\gamma_{xz}^{(2)} \tag{9}$$

where

$$\varepsilon_{xx}^{(0)} = \frac{\partial u}{\partial x},\ \varepsilon_{xx}^{(1)} = \frac{\partial \psi}{\partial x},\ \varepsilon_{xx}^{(3)} = -\alpha(\frac{\partial \psi}{\partial x} + \frac{\partial^2 w}{\partial x^2}) \tag{10}$$

$$\gamma_{xz}^{(0)} = \frac{\partial w}{\partial x} + \psi,\ \gamma_{xz}^{(2)} = -\beta(\frac{\partial w}{\partial x} + \psi) \tag{11}$$

And $\beta = \frac{4}{h^2}$.

According to the defined electric potential in Eq. (7), the non-zero components of electric field (E_x, E_z) can be obtained as:

$$E_x = -\Phi_{,x} = \cos(\xi z)\frac{\partial \phi}{\partial x},$$
$$E_z = -\Phi_{,z} = -\xi \sin(\xi z)\phi - \frac{2V}{h} \tag{12}$$

The Hamilton's principle can be stated in the following form to obtain the governing equations of motion,:

$$\int_0^t \delta(\Pi_S + \Pi_W)\, dt = 0 \tag{13}$$

where Π_S is strain energy and Π_W is work done by external applied forces. The first variation of strain energy Π_S can be calculated as:

$$\delta\Pi_S = \int_0^L \int_{-h/2}^{h/2} (\sigma_{xx}\,\delta\varepsilon_{xx} + \sigma_{xz}\,\delta\gamma_{xz} - D_x\,\delta E_x - D_z\,\delta E_z)\,dz\,dx \tag{14}$$

Substituting Eqs. (8) and (9) into Eq. (14) yields:

$$\delta\Pi_S == \int_0^L (N\delta\varepsilon_{xx}^{(0)} + M\delta\varepsilon_{xx}^{(1)} + P\delta\varepsilon_{xx}^{(3)} + Q\delta\gamma_{xz}^{(0)} + R\delta\gamma_{xz}^{(2)})\,dx$$
$$+ \int_0^L \int_{-h/2}^{h/2} \left(-D_x \cos(\xi z)\,\delta\left(\frac{\partial \phi}{\partial x}\right) + D_z \xi \sin(\xi z)\,\delta\phi \right) dz\,dx \tag{15}$$

in which N, M and Q are the axial force, bending moment and shear force resultants, respectively. Relations between the stress resultants and stress component used in Eq. (15) are defined as:

$$N = \int_A \sigma_{xx}\, dA,\ M = \int_A \sigma_{xx} z\, dA,\ P = \int_A \sigma_{xx} z^3 dA$$
$$Q = \int_A \sigma_{xz}\, dA,\ R = \int_A \sigma_{xz} z^2\, dA \tag{16}$$

The work done due to external electric voltage, Π_W, can be written in the form:

$$\Pi_W = \int_0^L ((N_E + N_b)\frac{\partial w}{\partial x}\frac{\partial \delta w}{\partial x} + q\,\delta w + f\,\delta u - N\delta\varepsilon_{xx}^{(0)} - \hat{M}\frac{\partial \delta\psi}{\partial x}$$
$$+ \alpha P \frac{\partial^2 \delta w}{\partial x^2} - \hat{Q}\delta\gamma_{xz}^{(0)} - k_w \delta w + k_p \frac{\partial^2 \delta w}{\partial x^2})dx \tag{17}$$

where $\hat{M} = M - \alpha P,\ \hat{Q} = Q - \beta R$ and $q(x)$ and $f(x)$ are the transverse and axial distributed loads and k_w and k_w are foundation parameters and N_E is normal forced due to external electric voltage (V) which is defined as:

$$N_E = -\int_{-h/2}^{h/2} e_{31} \frac{2V}{h} dz \tag{18}$$

For a FGPM nanobeam exposed to electro-mechanical loading in the one dimensional case, the nonlocal constitutive relations (5a) and (5b) may be rewritten as:

$$\sigma_{xx} - (e_0 a)^2 \frac{\partial^2 \sigma_{xx}}{\partial x^2} = c_{11}\varepsilon_{xx} - e_{31}E_z \tag{19}$$

$$\sigma_{xz} - (e_0 a)^2 \frac{\partial^2 \sigma_{xz}}{\partial x^2} = c_{55}\gamma_{xz} - e_{15}E_x \tag{20}$$

$$D_x - (e_0 a)^2 \frac{\partial^2 D_x}{\partial x^2} = e_{15}\gamma_{xz} + k_{11}E_x \tag{21}$$

$$D_z - (e_0 a)^2 \frac{\partial^2 D_z}{\partial x^2} = e_{31}\varepsilon_{xx} + k_{33}E_z \tag{22}$$

Inserting Eqs. (15) and (17) in Eq. (13) and integrating by parts, and gathering the coefficients of δu, δw, $\delta\psi$ and $\delta\phi$, the following governing equations are obtained:

$$\frac{\partial N}{\partial x} + f = 0 \tag{23}$$

$$\frac{\partial M}{\partial x} - Q = 0 \tag{24}$$

$$\frac{\partial \bar{Q}}{\partial x} + q - (N_E + N_b)\frac{\partial^2 w}{\partial x^2} + \alpha \frac{\partial^2 P}{\partial x^2} - k_w w + k_p \frac{\partial^2 w}{\partial x^2} = 0 \tag{25}$$

$$\int_{-h/2}^{h/2} \left(\cos(\xi z)\frac{\partial D_x}{\partial x} + \xi \sin(\xi z) D_z \right) dz = 0 \tag{26}$$

By integrating Eqs. (19)-(22), over the beam's cross-section area, the force-strain and the moment-strain of the nonlocal third order Reddy FGP beam theory can be obtained as follows:

$$N - \mu \frac{\partial^2 N}{\partial x^2} = A_{xx}\frac{\partial u}{\partial x} + B_{xx}\frac{\partial \psi}{\partial x} - \alpha E_{xx}\left(\frac{\partial \psi}{\partial x} + \frac{\partial^2 w}{\partial x^2}\right) + A_{31}^e \phi - N_E \tag{27}$$

$$M - \mu \frac{\partial^2 M}{\partial x^2} = B_{xx}\frac{\partial u}{\partial x} + D_{xx}\frac{\partial \psi}{\partial x} - \alpha F_{xx}\left(\frac{\partial \psi}{\partial x} + \frac{\partial^2 w}{\partial x^2}\right) + E_{31}\phi \tag{28}$$

$$P - \mu \frac{\partial^2 P}{\partial x^2} = E_{xx}\frac{\partial u}{\partial x} + F_{xx}\frac{\partial \psi}{\partial x} - \alpha H_{xx}\left(\frac{\partial \psi}{\partial x} + \frac{\partial^2 w}{\partial x^2}\right) + F_{31}\phi \tag{29}$$

$$Q - \mu \frac{\partial^2 Q}{\partial x^2} = (A_{xz} - \beta D_{xz})\left(\frac{\partial w}{\partial x} + \psi\right) - E_{15}\frac{\partial \phi}{\partial x} \tag{30}$$

$$R - \mu \frac{\partial^2 R}{\partial x^2} = (D_{xz} - \beta F_{xz})\left(\frac{\partial w}{\partial x} + \psi\right) - F_{15}\frac{\partial \phi}{\partial x} \tag{31}$$

$$\int_{-h/2}^{h/2} \left\{ D_x - \mu \frac{\partial^2 D_x}{\partial x^2} \right\} \cos(\xi z) dz = (E_{15} - \beta F_{15})\left(\frac{\partial w}{\partial x} + \psi\right) + F_{11}\frac{\partial \phi}{\partial x} \tag{32}$$

$$\int_{-h/2}^{h/2} \left\{ D_z - \mu \frac{\partial^2 D_z}{\partial x^2} \right\} \xi \sin(\xi z) dz = A_{31}^e \frac{\partial u}{\partial x} + (E_{31} - \alpha F_{31})\frac{\partial \psi}{\partial x} - \alpha F_{31}\frac{\partial^2 w}{\partial x^2} - F_{33}\phi \tag{33}$$

where $\mu = (e_0 a)^2$ and quantities used in above equations are defined as:

$$\left\{A_{xx}, B_{xx}, D_{xx}, E_{xx}, F_{xx}, H_{xx}\right\} = \int_{-h/2}^{h/2} c_{11}\left\{1, z, z^2, z^3, z^4, z^6\right\} dz \tag{34}$$

$$\left\{A_{xz}, D_{xz}, F_{xz}\right\} = \int_{-h/2}^{h/2} c_{55}\left\{1, z^2, z^4\right\} dz \tag{35}$$

$$\left\{A_{31}^e, E_{31}, F_{31}\right\} = \int_{-h/2}^{h/2} e_{31}\left\{\xi \sin(\xi z), z\xi \sin(\xi z), z^3 \xi \sin(\xi z)\right\} dz \tag{36}$$

$$\left\{E_{15}, F_{15}\right\} = \int_{-h/2}^{h/2} e_{15}\left\{\cos(\xi z), z^2 \cos(\xi z)\right\} dz \tag{37}$$

$$\left\{F_{11}, F_{33}\right\} = \int_{-h/2}^{h/2} \left\{k_{11}\cos^2(\xi z), k_{33}\xi^2 \sin^2(\xi z)\right\} dz \tag{38}$$

The explicit relation of the nonlocal normal force can be derived by substituting for the second derivative of N from Eq.(23) into Eq.(27) as follows:

$$N = A_{xx}\frac{\partial u}{\partial x} + K_{xx}\frac{\partial \psi}{\partial x} - \alpha E_{xx}\frac{\partial^2 w}{\partial x^2} + A_{31}^e \phi - N_E + \mu(-\frac{\partial f}{\partial x}) \tag{39}$$

Omitting $\hat{Q}$ from Eqs. (24) and (25), we obtain the following equation:

$$\frac{\partial^2 \bar{M}}{\partial x^2} = -\alpha\frac{\partial^2 P}{\partial x^2} - q + (N_E + N_b)\frac{\partial^2 w}{\partial x^2} + k_w w - k_p\frac{\partial^2 w}{\partial x^2} \tag{40}$$

Also the explicit relation of the nonlocal bending moment can be derived by substituting for the second derivative of M from Eq. (24) into Eq. (28) and using Eqs. (28) and (29) as follows:

$$\begin{aligned}\hat{M} &= K_{xx}\frac{\partial u}{\partial x} + I_{xx}\frac{\partial \psi}{\partial x} - \alpha J_{xx}(\frac{\partial \psi}{\partial x} + \frac{\partial^2 w}{\partial x^2}) + (E_{31} - \alpha F_{31})\phi + \mu(-\alpha\frac{\partial^2 P}{\partial x^2} - q \\ &+ \frac{\partial}{\partial x}((N_E + N_b)\frac{\partial w}{\partial x}) + k_w w - k_p\frac{\partial^2 w}{\partial x^2})\end{aligned} \tag{41}$$

where

$$K_{xx} = B_{xx} - \alpha E_{xx},\ I_{xx} = D_{xx} - \alpha F_{xx},\ J_{xx} = F_{xx} - \alpha H_{xx} \tag{42}$$

By substituting for the second derivative of $\hat{Q}$ from Eq. (25) into Eq. (30), and using Eqs. (30) and (31) the following expression for the nonlocal shear force is derived:

$$\hat{Q} = \bar{A}_{xz}(\frac{\partial w}{\partial x} + \psi) - (E_{15} - \beta F_{15})\frac{\partial \phi}{\partial x} + \mu((N_E + N_b)\frac{\partial^3 w}{\partial x^3} - \alpha\frac{\partial^3 P}{\partial x^3} - \frac{\partial q}{\partial x} + k_w\frac{\partial w}{\partial x} - k_p\frac{\partial^3 w}{\partial x^3}) \tag{43}$$

Where

$$\bar{A}_{xz} = A^*_{xz} - \beta I^*_{xz},\ A^*_{xz} = A_{xz} - \beta D_{xz},\ I^*_{xz} = D_{xz} - \beta F_{xz} \tag{44}$$

Now we use M and Q from Eqs. (41) and (43) and the identity

$$\alpha\frac{\partial^2}{\partial x^2}(P - \mu\frac{\partial^2 P}{\partial x^2}) = \alpha(E_{xx}\frac{\partial^3 u}{\partial x^3} + F_{xx}\frac{\partial^3 \psi}{\partial x^3} - \alpha H_{xx}(\frac{\partial^3 \psi}{\partial x^3} + \frac{\partial^4 w}{\partial x^4}) + F_{31}\frac{\partial^2 \phi}{\partial x^2}) \tag{45}$$

It must be cited that inserting Eq. (26) into Eqs. (32) and (33), does not provide an explicit expressions for D_x and D_z . To overcome this problem, by using Eqs. (32) and (33), Eq. (26) can be re-expressed in terms of u, w , ψ and ϕ . For a higher order FGP nanobeam by substituting for N , M and Q from Eqs. (39),(41) and (43) into Eqs. (23)-(25) the nonlocal governing equations can be written as:

$$A_{xx}\frac{\partial^2 u}{\partial x^2} + K_{xx}\frac{\partial^2 \psi}{\partial x^2} - \alpha E_{xx}\frac{\partial^3 w}{\partial x^3} + A_{31}^e\frac{\partial \phi}{\partial x} + \mu(-\frac{\partial^2 f}{\partial x^2}) + f = 0 \tag{46}$$

$$\begin{aligned}&K_{xx}\frac{\partial^2 u}{\partial x^2} + I_{xx}\frac{\partial^2 \psi}{\partial x^2} - \alpha J_{xx}(\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^3 w}{\partial x^3}) - \bar{A}_{xz}\left(\varphi + \frac{\partial w}{\partial x}\right) + (E_{31} - \alpha F_{31})\phi \\ &+(E_{15} - \beta F_{15})\frac{\partial \phi}{\partial x} = 0\end{aligned} \tag{47}$$

$$\begin{aligned}&\bar{A}_{xz}\left(\frac{\partial \psi}{\partial x} + \frac{\partial^2 w}{\partial x^2}\right) + \mu((N_E + N_b)\frac{\partial^4 w}{\partial x^4} - \frac{\partial^2 q}{\partial x^2} + k_w\frac{\partial^2 w}{\partial x^2} - k_p\frac{\partial^4 w}{\partial x^4}) + q - (N_E + N_b)\frac{\partial^2 w}{\partial x^2} \\ &-(E_{15} - \beta F_{15})\frac{\partial \phi}{\partial x} - k_w w + k_p\frac{\partial^2 w}{\partial x^2} + \alpha(E_{xx}\frac{\partial^3 u}{\partial x^3} + J_{xx}\frac{\partial^3 \psi}{\partial x^3} - \alpha H_{xx}\frac{\partial^4 w}{\partial x^4} + F_{31}\frac{\partial^2 \phi}{\partial x^2}) = 0\end{aligned} \tag{48}$$

$$(E_{15} - \beta F_{15})(\frac{\partial^2 w}{\partial x^2} + \frac{\partial \psi}{\partial x}) + F_{11}\frac{\partial^2 \phi}{\partial x^2} + A_{31}^e\frac{\partial u}{\partial x} + (E_{31} - \alpha F_{31})\frac{\partial \psi}{\partial x} - \alpha F_{31}\frac{\partial^2 w}{\partial x^2} - F_{33}\phi = 0 \tag{49}$$

3. Solution Procedure

Here, on the basis the Navier method, an analytical solution of the governing equations for buckling of a simply supported FGP nanobeam is presented. To satisfy governing equations of motion and the simply supported boundary condition, the displacement variables are adopted to be of the form:

$$u(x,t) = \sum_{n=1}^{\infty} U_n \cos(\frac{n\pi}{L}x)e^{i\omega_n t} \tag{50}$$

$$w(x,t) = \sum_{n=1}^{\infty} W_n \sin(\frac{n\pi}{L}x)e^{i\omega_n t} \tag{51}$$

$$\psi(x,t) = \sum_{n=1}^{\infty} \Psi_n \cos(\frac{n\pi}{L}x)e^{i\omega_n t} \tag{52}$$

$$\phi(x,t) = \sum_{n=1}^{\infty} \Phi_n \sin(\frac{n\pi}{L}x)e^{i\omega_n t} \tag{53}$$

where U_n, W_n, Ψ_n and Φ_n are the unknown Fourier coefficients to be determined for each n value. The boundary conditions for simply supported FGP beam can be identified as:

$$u(0) = 0, \quad \frac{\partial u}{\partial x}(L) = 0, \quad w(0) = w(L) = 0 \tag{54}$$
$$\frac{\partial \psi}{\partial x}(0) = \frac{\partial \psi}{\partial x}(L) = 0, \quad \phi(0) = \phi(L) = 0$$

Inserting Eqs. (50)-(53) into Eqs. (46)-(49), respectively, yields:

Inserting Eqs. (50)-(53) into Eqs. (46)-(49), respectively, yields:

$$(-A_{xx}(\frac{n\pi}{l})^2)U_n + (-K_{xx}(\frac{n\pi}{l})^2)\psi_n + (\alpha E_{xx}(\frac{n\pi}{l})^3)W_n + (-A_{31}^e(\frac{n\pi}{l}))\phi_n = 0 \tag{55}$$

$$\begin{aligned}&(-K_{xx}(\frac{n\pi}{l})^2)U_n + (-I_{xx}(\frac{n\pi}{l})^2 + \alpha J_{xx}(\frac{n\pi}{l})^2 - \bar{A}_{xz})\psi_n + (\alpha J_{xx}(\frac{n\pi}{l})^3 - \bar{A}_{xz}(\frac{n\pi}{l}))W_n \\ &+((E_{31} - \alpha F_{31}) + (E_{15} - \beta F_{15})(\frac{n\pi}{l}))\phi_n = 0\end{aligned} \tag{56}$$

$$\begin{aligned}&(\alpha E_{xx}(\frac{n\pi}{l})^3)U_n + (-\bar{A}_{xz}(\frac{n\pi}{l}) + J_{xx}(\frac{n\pi}{l})^3)\psi_n + (N_E + N_b)(\frac{n\pi}{l})^2(1+\mu(\frac{n\pi}{l})^2) - \bar{A}_{xz}(\frac{n\pi}{l})^2 - \alpha^2 H_{xx}(\frac{n\pi}{l})^4 \\ &-k_w(1+\mu(\frac{n\pi}{l})^2) - k_p(\frac{n\pi}{l})^2(1+\mu(\frac{n\pi}{l})^2))W_n + (-(E_{15} - \beta F_{15})(\frac{n\pi}{l}) - F_{31}(\frac{n\pi}{l})^2)\phi_n = 0\end{aligned} \tag{57}$$

$$\begin{aligned}&\left(-A_{31}^e(\frac{n\pi}{L})\right)U_n - \left(((E_{15} - \beta F_{15}) - \alpha F_{31})(\frac{n\pi}{L})^2\right)W_n - \left((E_{15} - \beta F_{15}) + (E_{31} - \alpha F_{31})(\frac{n\pi}{L})\right)\Psi_n \\ &-\left(F_{11}(\frac{n\pi}{L})^2 + F_{33}\right)\Phi_n = 0\end{aligned} \tag{58}$$

By setting the determinant of the coefficient matrix of the above equations, the nontrivial analytical solutions can be obtained from the following equations:

$$\{[K]\}\begin{Bmatrix} U_n \\ W_n \\ \Psi_n \\ \Phi_n \end{Bmatrix} = 0 \qquad (59)$$

where $[K]$ denotes the stiffness matrix. By setting this polynomial to zero, we can find buckling loads of the FGP nanobeam exposed to electrical loading.

4. Results and Discussion

This section is devoted to explore the buckling behavior of nanoscale FGP beams on elastic substrate incorporating shear deformation effects. Effects of applied voltage, geometrical parameters, scale parameter and foundation constants will on buckling load will be discussed. Here, a FGP beam composed of PZT-4 and PZT-5H, with electro-mechanical material properties listed in Table 1, is supposed. The beam geometry has the following dimensions: L (length) = 10 nm and h (thickness) = varied. Also, the following relation is described to calculate the non-dimensional buckling loads as well as foundation parameters:

$$N_{bcr} = N_b \frac{L^2}{(c_{11}I)_{PZT-4}},\ K_w = k_w \frac{L^4}{(c_{11}I)_{PZT-4}},\quad K_p = k_p \frac{L^2}{(c_{11}I)_{PZT-4}} \qquad (60)$$

In which $I = \mathrm{h}^3/12$ denote the moment of inertia of the cross section of the nanobeam. Table 2 compares dimensionless buckling loads of the present model with those of nonlocal Reddy beams, because there are no available data for the buckling loads of FGP nanobeams based on the nonlocal elasticity theory. For comparison study, the material selection is performed as follows: E_m = 70 GPa, ν_m = 0.3, for Steel and E_c = 390 GPa and ν_c = 0.3 for Alumina.

Tables 3-6, present the influences of elastic foundation parameters (K_w, K_p), nonlocal parameter (μ), electric voltage (V), gradient index (p) and slenderness ratio on the non-dimensional buckling load of the S-S FGP nanobeams. It must be cited that nonlocal parameter weakens the nanobeam structure, so it has a remarkable decreasing influence on the non-dimensional buckling loads. Also, it is found that existence of elastic foundation makes the beam more rigid and hence the dimension buckling loads rise. In addition, it is observed from these tables that the buckling load results for negative voltage are higher than positive voltages. In a special case, when electric voltage is equal to 0V the variation of buckling loads with slenderness ratio is not considerable. But for negative and positive voltages, with the rise of slenderness ratio the buckling loads increase and decrease, respectively.

In Figs. 2-3 the effects of Winkler and Pasternak foundations on the variations of the non-dimensional buckling load of FG piezoelectric nanobeams with the power-law index are illustrated for various values of external voltages ($V = -0.5, -0.25, 0, +0.25, +0.5$) at nonlocal parameter $\mu = 2$ and slenderness ratio $L/h = 20$. It is observable from these figures that for all values of Winkler or Pasternak parameter the non-dimensional buckling load decreases dramatically for lower values of gradient indexes, and then continues to decline with non-sensitive variation for higher values of power-law index. Moreover, it is seen that the reduction in the dimensionless buckling load for positive voltages occurs more significantly compared to negative voltages which shows notability of the sign of external electric voltage. Also, it should be mentioned that with an increase in Winkler or Pasternak parameter, non-dimensional buckling load begins to decline with higher values versus the power-law index.

Figs. 4 and 5 shows the influence of electric voltage on the variations of the non-dimensional buckling load with respect to Winkler and Pasternak foundation parameters, respectively, for different nonlocal parameters at slenderness ratio L/h=20 and power-law index p=1. It is seen that for both negative and positive voltages as the Winkler or Pasternak parameter rises the buckling load increases due to the stiffening influence of elastic foundation on the structure of the beam. Also, it is found that at a fixed Winkler or Pasternak parameter when the voltage changes from $V = -0.5$ to $V = +0.5$ the dimensionless buckling load of FGP nanobeams decreases. Also, it can be seen that at a constant electric voltage the rise of the dimensionless buckling load with respect to Pasternak parameter is more significant than Winker parameter.

The variations of the dimensionless buckling loads of FGM piezoelectric nanobeams with respect to electric voltage for various foundation and nonlocal parameters at L/h=20 and p=1 are plotted in Figs. 6-7. As a result, for all values of Winkler or Pasternak parameters when the electric voltage rises from $V = -1$ to $V = +1$ the dimensionless buckling load reduce. It is also observed from the figures that, with the rise of Winkler and Pasternak parameters the variations of buckling loads decrease because the flexibility of the beam reduces.

The effect of material composition (power-law exponent) on the variation of dimensionless buckling load of FGP nanobeams versus external electric voltage with and without elastic foundations at $L/h = 20$ and $\mu = 2(\mathrm{nm})^2$ is depicted in Fig.8. As an important observation, at the negative voltages, for example V=-1, the values of buckling loads for various gradient indexes are very close together but at positive electric voltages the differences of buckling loads rise. Due to the fact that increase of power-law exponent makes the beam more flexible, the reduction of buckling loads for higher power-law exponents is more significant than lower ones.

The influence of slenderness ratio and elastic foundation on the dimensionless buckling load of FGP nanobeams with various gradient indices when $\mu = 2(\mathrm{nm})^2$ and gradient index p=0.5 is presented in Fig.9. It can be seen that slenderness ratio has an important influence on the non-dimensional buckling loads especially for its higher values. Moreover, an important observation is that the negative/positive electric voltages increases /decrease the buckling loads of the piezoelectric nanobeams. This is due to the axial compressive and tensile forces produced in the FGP nanobeams via the applied positive and negative voltages, respectively. So, zero external electric voltage $V=0$ makes no compressive or tensile force and will not affect the dimensionless buckling load with changing of slenderness ratio.

Table 1. Electro-mechanical coefficients of material properties for PZT-4 and PZT-5H [29].

Properties	PZT-4	PZT-5H
c_{11} (GPa)	81.3	60.6
c_{55} (GPa)	25.6	23.0
e_{31} (Cm^{-2})	-10.0	-16.604
e_{15} (Cm^{-2})	40.3248	44.9046
k_{11} ($C^2 m^{-2} N^{-1}$)	0.6712e-8	1.5027e-8
k_{33} ($C^2 m^{-2} N^{-1}$)	1.0275e-8	2.554e-8

Table 2. Comparison of the non-dimensional buckling load for a FG nanobeam with various power-law index (L/h =20).

p	Nonlocal parameter							
	μ =1		μ =2		μ =3		μ =4	
	RBT [24]	Present	RBT [24]	Present	RBT [24]	Present	RBT [24]	Present
0	8.9258	8.925759	8.1900	8.190046	7.5663	7.566381	7.0309	7.030978
0.1	9.7778	9.777865	8.9719	8.971916	8.2887	8.288712	7.7021	7.702196
0.2	10.3898	10.389845	9.5334	9.533453	8.8074	8.807489	8.1842	8.184264
0.5	11.4944	11.494448	10.5470	10.547009	9.7438	9.743863	9.0543	9.054379
1	12.3709	12.370918	11.3512	11.351234	10.4869	10.486847	9.7447	9.744790
2	13.1748	13.174885	12.0889	12.088934	11.1683	11.168372	10.3781	10.378089
5	14.2363	14.236343	13.0629	13.062900	12.0682	12.068171	11.2142	11.214218

Table 3. Influence of elastic foundation and external electric voltage on the non-dimensional buckling load of a FGP nanobeam ($\mu=0(nm)^2$).

(K_p,K_w)	L/h	V=-0.5			V=0			V=+0.5		
		p=0.2	p=1	p=5	p=0.2	p=1	p=5	p=0.2	p=1	p=5
(0,0)	20	11.7966	11.3101	11.0785	10.4858	9.73938	9.24789	9.17502	8.16866	7.41724
	25	13.0536	12.8144	12.8300	10.4935	9.74657	9.25456	7.93337	6.67876	5.67906
	30	14.9216	15.0517	15.4367	10.4977	9.75050	9.25820	6.07381	4.44933	3.07975
(5,25)	20	19.3296	18.8431	18.6116	18.0188	17.2724	16.7809	16.7081	15.7017	14.9503
	25	20.5866	20.3474	20.3631	18.0265	17.2796	16.7876	15.4664	14.2118	13.2121
	30	22.4546	22.5847	22.9697	18.0307	17.2835	16.7912	13.6068	11.9824	10.6128
(5,50)	20	21.8626	21.3762	21.1446	20.5519	19.8054	19.3139	19.2411	18.2347	17.4833
	25	23.1197	22.8804	22.8961	20.5595	19.8126	19.3206	17.9994	16.7448	15.7451
	30	24.9876	25.1177	25.5027	20.5638	19.8166	19.3243	16.1399	14.5154	13.1458
(10,25)	20	24.3296	23.8431	23.6116	23.0188	22.2724	21.7809	21.7081	20.7017	19.9503
	25	25.5866	25.3474	25.3631	23.0265	22.2796	21.7876	20.4664	19.2118	18.2121
	30	27.4546	27.5847	27.9697	23.0307	22.2835	21.7912	18.6068	16.9824	15.6128
(10,50)	20	26.8626	26.3762	26.1446	25.5519	24.8054	24.3139	24.2411	23.2347	22.4833
	25	28.1197	27.8804	27.8961	25.5595	24.8126	24.3206	22.9994	21.7448	20.7451
	30	29.9876	30.1177	30.5027	25.5638	24.8166	24.3243	21.1399	19.5154	18.1458

Table 4. Influence of elastic foundation and external electric voltage on the non-dimensional buckling load of a FGP nanobeam ($\mu = 1(nm)^2$)

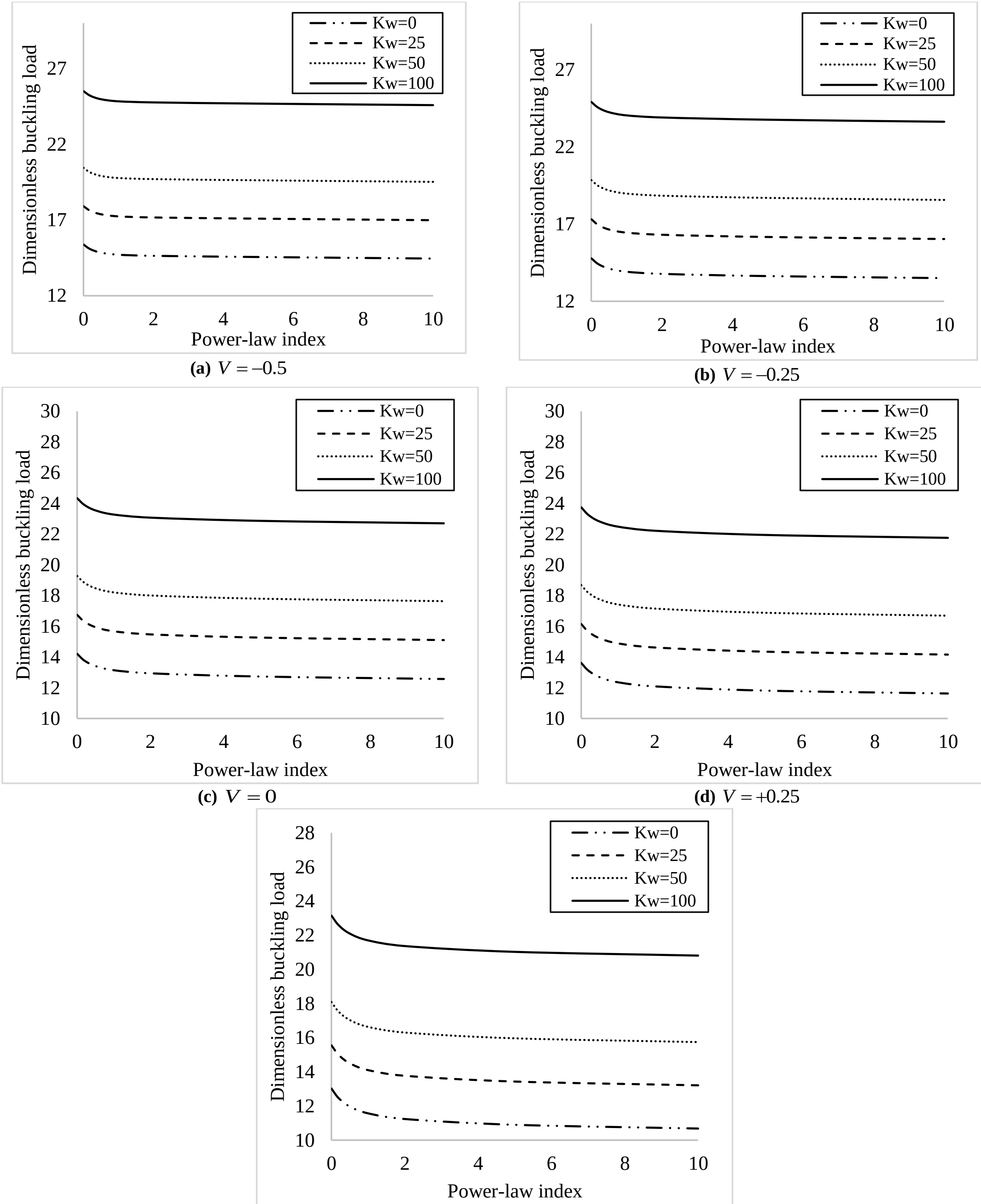
(K_p, K_w)	L/h	V=-0.5			V=0			V=+0.5		
		p=0.2	p=1	p=5	p=0.2	p=1	p=5	p=0.2	p=1	p=5
(0,0)	20	10.8546	10.4352	10.2478	9.54386	8.86449	8.41715	8.23308	7.29377	6.58650
	25	12.1110	11.9388	11.9987	9.55085	8.87103	8.42322	6.99074	5.80323	4.84773
	30	13.9786	14.1758	14.6050	9.55468	8.87461	8.42654	5.13080	3.57345	2.24809
(5,25)	20	18.3877	17.9682	17.7808	17.0769	16.3975	15.9502	15.7661	14.8268	14.1195
	25	19.6440	19.4719	19.5317	17.0839	16.4041	15.9562	14.5238	13.3363	12.3808
	30	21.5116	21.7088	22.1380	17.0877	16.4076	15.9596	12.6638	11.1065	9.78111
(5,50)	20	20.9207	20.5013	20.3139	19.6099	18.9305	18.4832	18.2991	17.3598	16.6526
	25	22.1770	22.0049	22.0648	19.6169	18.9371	18.4893	17.0568	15.8693	14.9138
	30	24.0446	24.2418	24.6710	19.6207	18.9407	18.4926	15.1969	13.6395	12.3141
(10,25)	20	23.3877	22.9682	22.7808	22.0769	21.3975	20.9502	20.7661	19.8268	19.1195
	25	24.6440	24.4719	24.5317	22.0839	21.4041	20.9562	19.5238	18.3363	17.3808
	30	26.5116	26.7088	27.1380	22.0877	21.4076	20.9596	17.6638	16.1065	14.7811
(10,50)	20	25.9207	25.5013	25.3139	24.6099	23.9305	23.4832	23.2991	22.3598	21.6526
	25	27.1770	27.0049	27.0648	24.6169	23.9371	23.4893	22.0568	20.8693	19.9138
	30	29.0446	29.2418	29.6710	24.6207	23.9407	23.4926	20.1969	18.6395	17.3141

Table 5. Influence of elastic foundation and external electric voltage on the non-dimensional buckling load of a FGP nanobeam ($\mu = 2(nm)^2$)

(K_p, K_w)	L/h	V=-0.5			V=0			V=+0.5		
		p=0.2	p=1	p=5	p=0.2	p=1	p=5	p=0.2	p=1	p=5
(0,0)	20	10.0680	9.70454	9.55401	8.75720	8.13382	7.72336	7.44642	6.56311	5.89271
	25	11.3237	11.2076	11.3044	8.76362	8.13983	7.72893	6.20350	5.07202	4.15343
	30	13.1910	13.4443	13.9104	8.76713	8.14311	7.73197	4.34325	2.84195	1.55352
(5,25)	20	17.6010	17.2376	17.0870	16.2902	15.6669	15.2564	14.9795	14.0961	13.4257
	25	18.8568	18.7407	18.8374	16.2966	15.6729	15.2620	13.7365	12.6051	11.6865
	30	20.7240	20.9773	21.4435	16.3002	15.6761	15.2650	11.8763	10.3750	9.08655
(5,50)	20	20.1340	19.7706	19.6201	18.8233	18.1999	17.7894	17.5125	16.6292	15.9588
	25	21.3898	21.2737	21.3705	18.8297	18.2059	17.7950	16.2696	15.1381	14.2195
	30	23.2571	23.5103	23.9765	18.8332	18.2092	17.7980	14.4093	12.9080	11.6196
(10,25)	20	22.6010	22.2376	22.0870	21.2902	20.6669	20.2564	19.9795	19.0961	18.4257
	25	23.8568	23.7407	23.8374	21.2966	20.6729	20.2620	18.7365	17.6051	16.6865
	30	25.7240	25.9773	26.4435	21.3002	20.6761	20.2650	16.8763	15.3750	14.0866
(10,50)	20	25.1340	24.7706	24.6201	23.8233	23.1999	22.7894	22.5125	21.6292	20.9588
	25	26.3898	26.2737	26.3705	23.8297	23.2059	22.7950	21.2696	20.1381	19.2195
	30	28.2571	28.5103	28.9765	23.8332	23.2092	22.7980	19.4093	17.9080	16.6196

Table 6. Influence of elastic foundation and external electric voltage on the non-dimensional buckling load of a FGP nanobeam($\mu = 3(nm)^2$)

(K_p, K_w)	L/h	V=-0.5			V=0			V=+0.5		
		p=0.2	p=1	p=5	p=0.2	p=1	p=5	p=0.2	p=1	p=5
(0,0)	20	9.40113	9.08516	8.96588	8.09035	7.51444	7.13523	6.77957	5.94372	5.30458
	25	10.6564	10.5878	10.7159	8.09627	7.51999	7.14038	5.53616	4.45218	3.56488
	30	12.5234	12.8242	13.3216	8.09952	7.52302	7.14319	3.67564	2.22186	0.96473
(5,25)	20	16.9342	16.6182	16.4989	15.6234	15.0475	14.6683	14.3126	13.4768	12.8376
	25	18.1894	18.1208	18.2489	15.6293	15.0530	14.6734	13.0692	11.9852	11.0979
	30	20.0564	20.3572	20.8547	15.6326	15.0561	14.6762	11.2087	9.75489	8.49777
(5,50)	20	19.4672	19.1512	19.0319	18.1564	17.5805	17.2013	16.8456	16.0098	15.3706
	25	20.7224	20.6539	20.7819	18.1623	17.5860	17.2064	15.6022	14.5182	13.6309
	30	22.5895	22.8902	23.3877	18.1656	17.5891	17.2092	13.7417	12.2879	11.0308
(10,25)	20	21.9342	21.6182	21.4989	20.6234	20.0475	19.6683	19.3126	18.4768	17.8376
	25	23.1894	23.1208	23.2489	20.6293	20.0530	19.6734	18.0692	16.9852	16.0979
	30	25.0564	25.3572	25.8547	20.6326	20.0561	19.6762	16.2087	14.7549	13.4978
(10,50)	20	24.4672	24.1512	24.0319	23.1564	22.5805	22.2013	21.8456	21.0098	20.3706
	25	25.7224	25.6539	25.7819	23.1623	22.5860	22.2064	20.6022	19.5182	18.6309
	30	27.5895	27.8902	28.3877	23.1656	22.5891	22.2092	18.7417	17.2879	16.0308



(a) $V = -0.5$

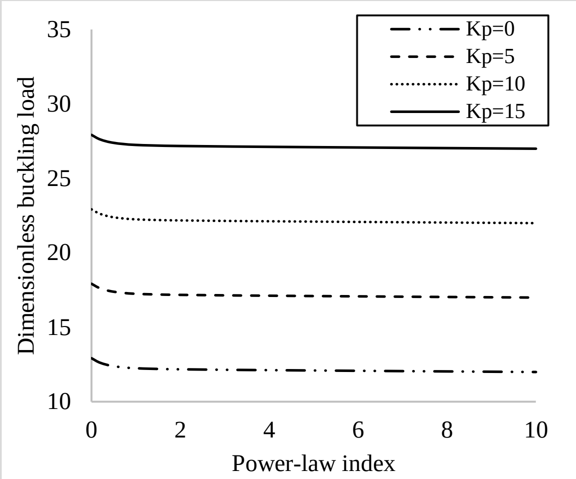
(b) $V = -0.25$

(c) $V = 0$

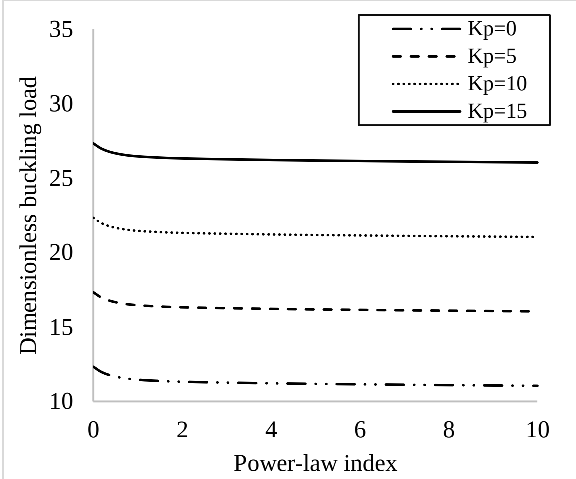
(d) $V = +0.25$

(e) $V = +0.5$

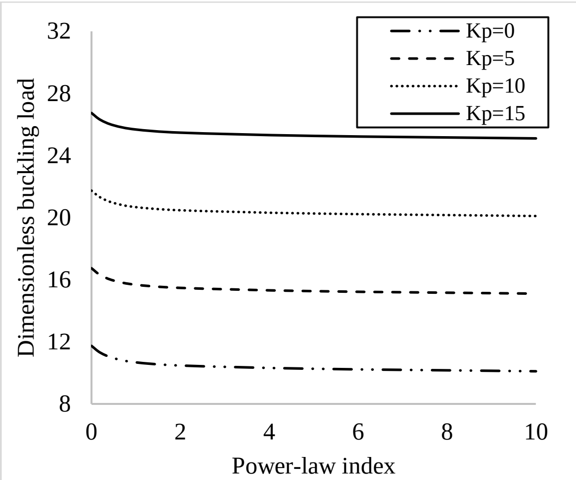
Fig. 2. Effect of Winkler parameter on the variation of dimensionless buckling load of the FGP nanobeam with respect to power-law index for different values of electric voltage ($L/h = 20, K_p = 5, \mu = 2$).



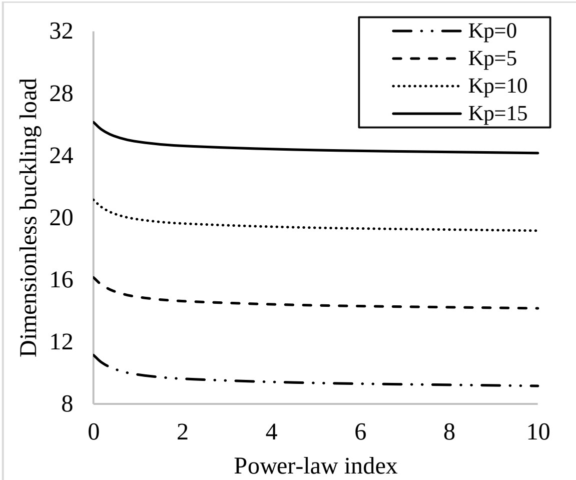
(a) $V=-0.5$



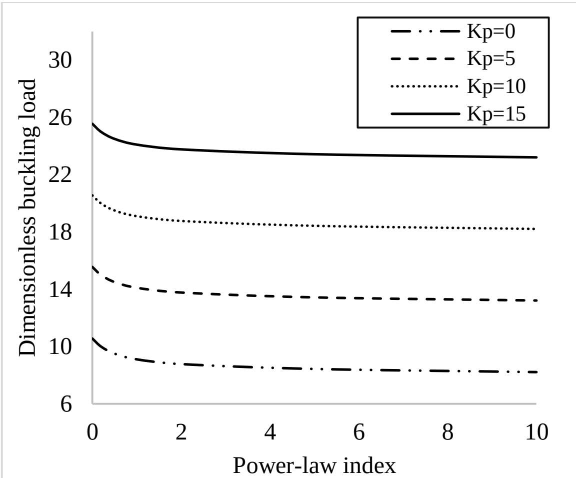
(b) $V=-0.25$



(c) $V=0$

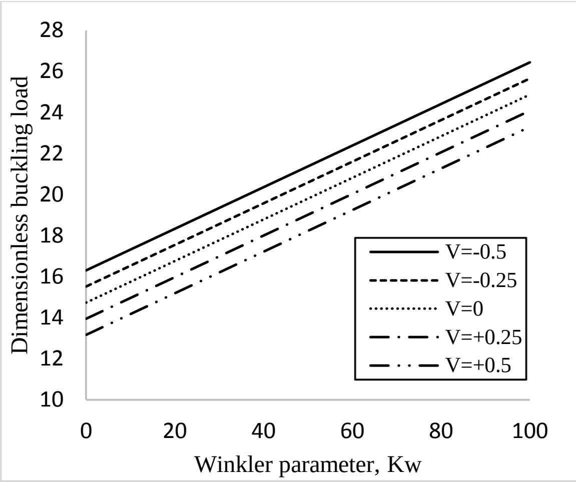


(d) $V=+0.25$

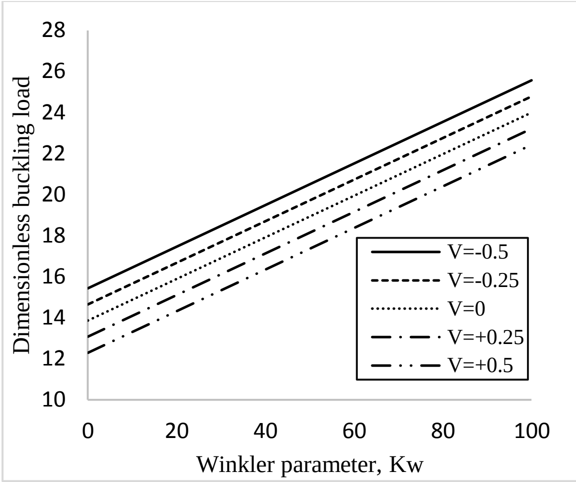


(e) $V=+0.5$

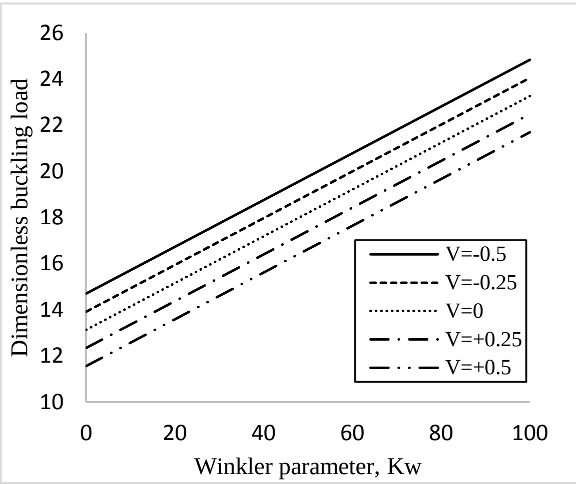
Fig. 3. Effect of Pasternak parameter on the variation of dimensionless buckling load of the FGP nanobeam with respect to power-law index for different values of electric voltage ($L/h=20, K_w=25, \mu=2$).



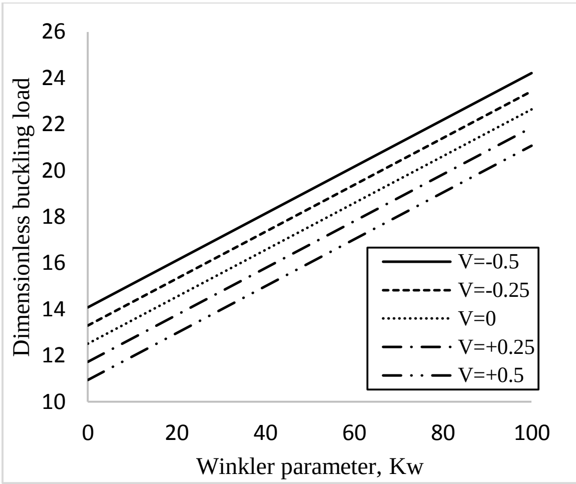
(a) $\mu = 0(\text{nm})^2$



(b) $\mu = 1(\text{nm})^2$

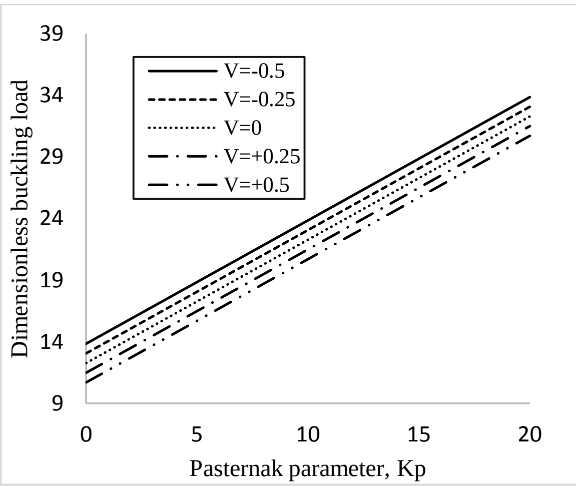


(c) $\mu = 2(\text{nm})^2$

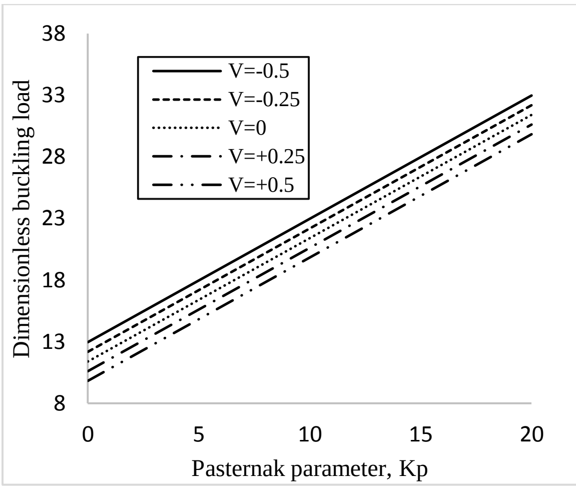


(d) $\mu = 3(\text{nm})^2$

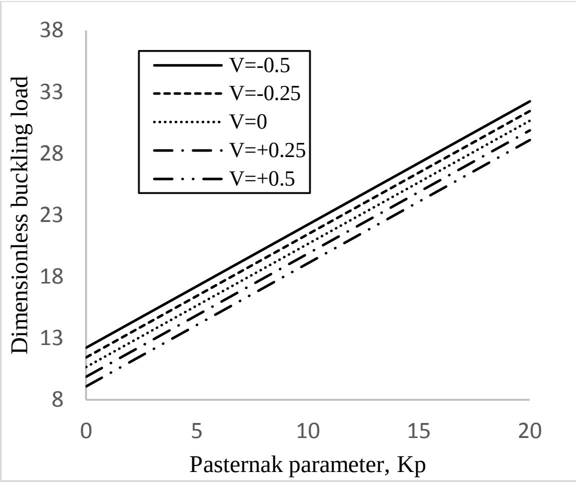
Fig. 4. Effect of electric voltage on the variation of dimensionless buckling load of the FGP nanobeam with respect to Winkler parameter for different values nonlocal parameter ($L/h = 20, K_p = 5, p = 1$).



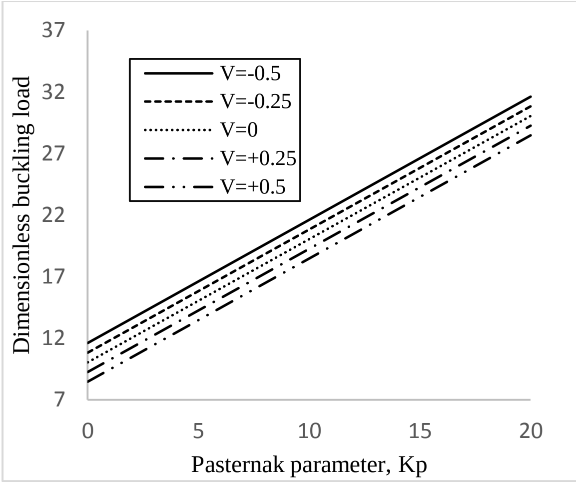
(a) $\mu = 0(\text{nm})^2$



(b) $\mu = 1(\text{nm})^2$

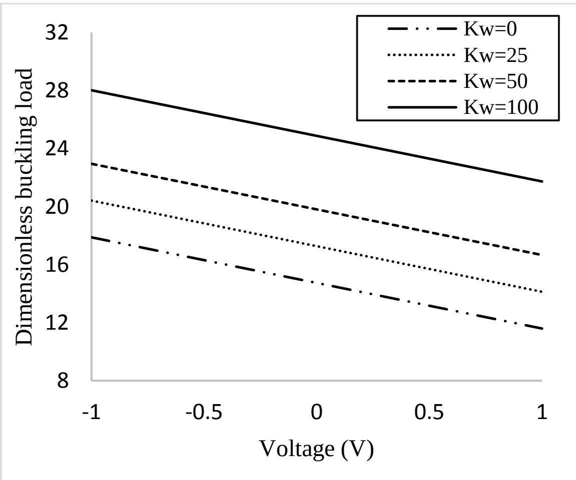


(c) $\mu = 2(\text{nm})^2$

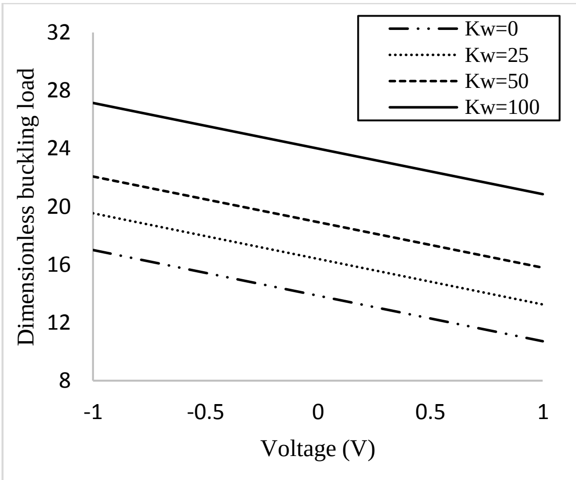


(d) $\mu = 3(\text{nm})^2$

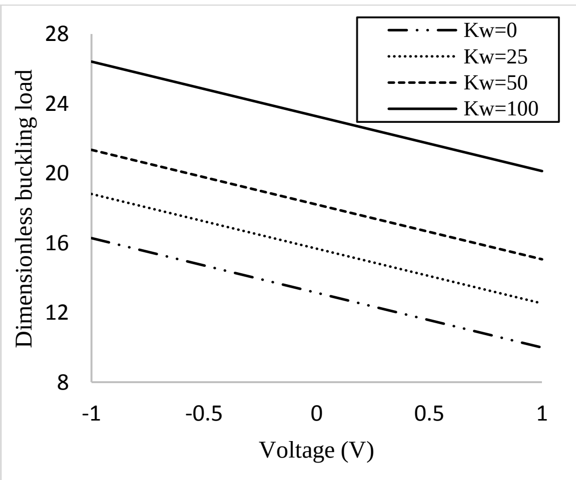
Fig. 5. Effect of electric voltage on the variation of dimensionless buckling load of the FGP nanobeam with respect to Pasternak parameter for different values nonlocal parameter ($L/h = 20, K_W = 25, p = 1$).



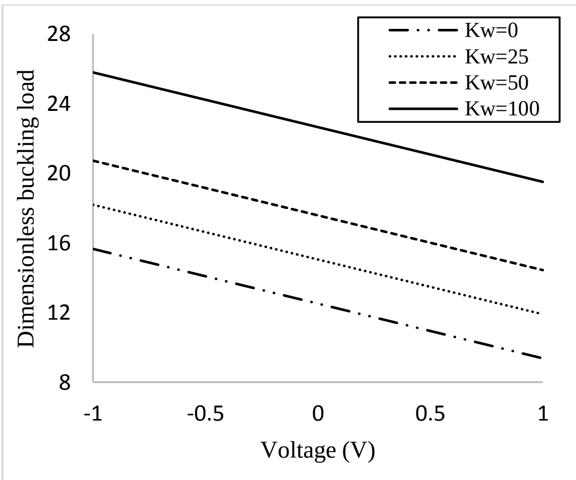
(a) $\mu = 0(\text{nm})^2$



(b) $\mu = 1(\text{nm})^2$

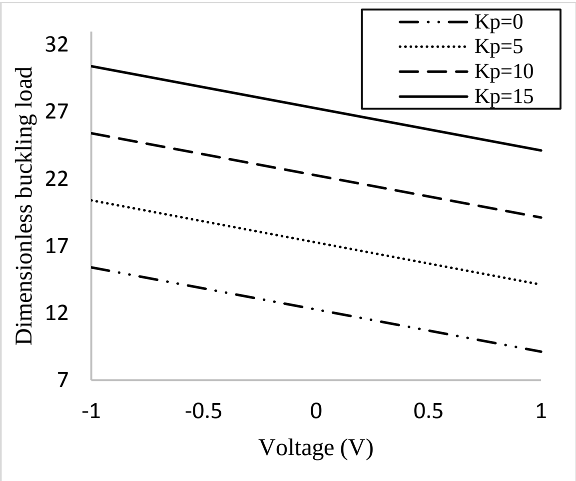


(c) $\mu = 2(\text{nm})^2$

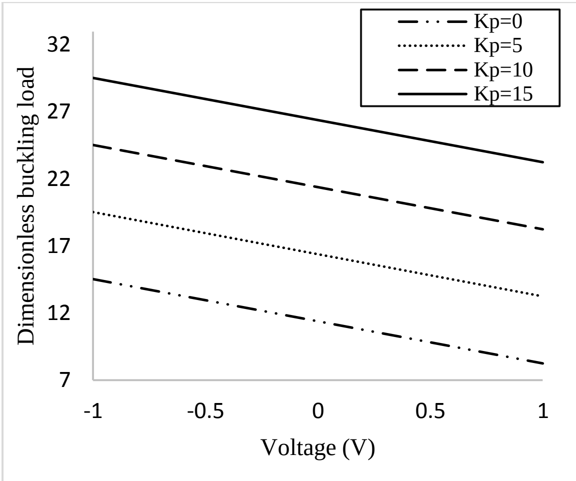


(d) $\mu = 3(\text{nm})^2$

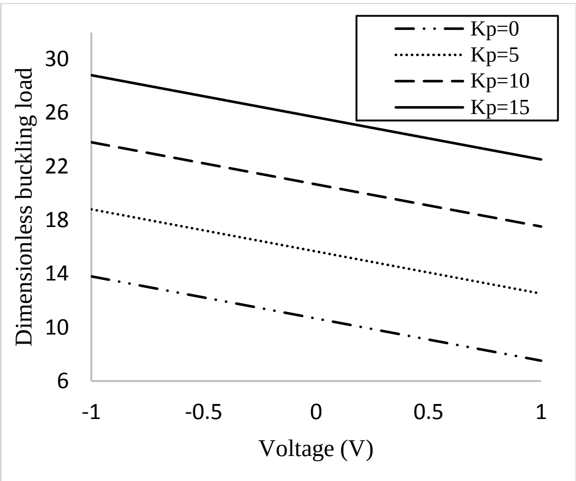
Fig. 6. Effect of Winkler parameter on the variation of dimensionless buckling load of the FGP nanobeam with respect to electric voltage for different values nonlocal parameter ($L/h = 20, K_p = 5, p = 1$).



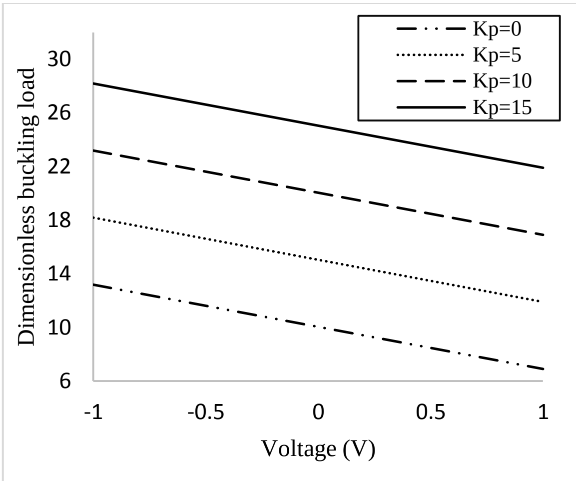
(a) $\mu = 0(\mathrm{nm})^2$



(b) $\mu = 1(\mathrm{nm})^2$

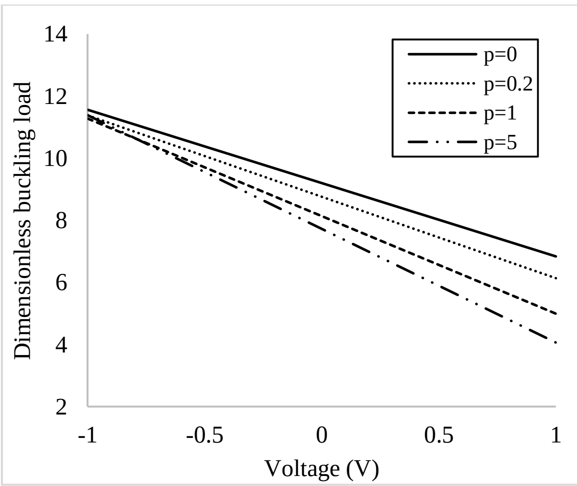


(c) $\mu = 2(\mathrm{nm})^2$

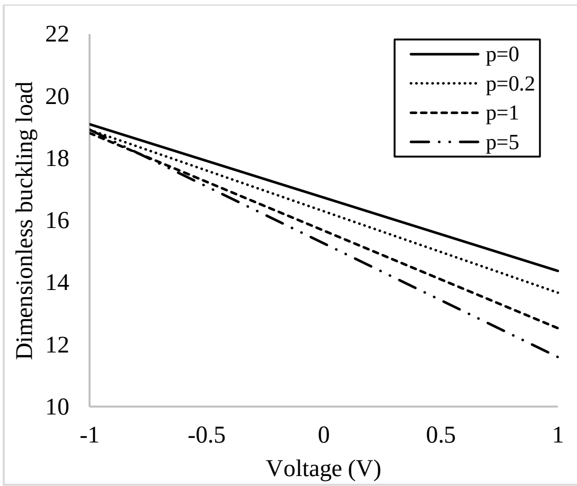


(d) $\mu = 3(\mathrm{nm})^2$

Fig. 7. Effect of Pasternak parameter on the variation of dimensionless buckling load of the FGP nanobeam with respect to electric voltage for different values nonlocal parameter ($L/h = 20, K_w = 25, p = 1$).

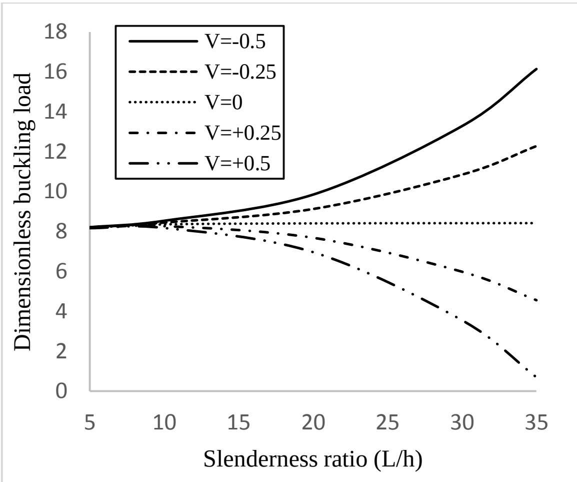


(a) $K_w = K_p = 0$

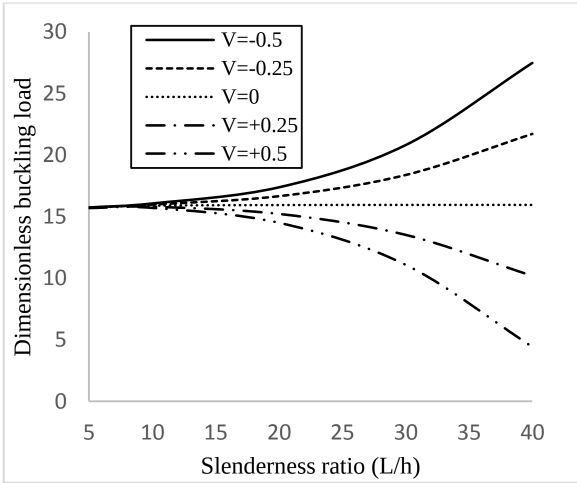


(b) $K_w = 25, K_p = 5$

Fig. 8. Effect of material composition on the variation of dimensionless buckling load of FGP nanobeam versus electric voltage with and without elastic foundation ($L/h = 20,\ \mu = 2$).



(a) $K_w = K_p = 0$



(b) $K_w = 25, K_p = 5$

Fig. 9. Effect of slenderness ratio on the variation of dimensionless buckling load of the FGP nanobeam for different values of electric voltage with and without elastic foundation ($L/h = 20,\ \mu = 2, p = 0.5$).

5. Conclusions

Buckling behavior of nonlocal functionally graded piezoelectric (FGP) beams on elastic substrate via a higher order beam model is examined. The present beam model takes into consideration the shear deformation effects needless of any shear correction factor. Employing power-law function, the gradation of material properties of the beam is described. A detailed parametric study is conducted to study the influences of the elastic foundation, nonlocal parameter, external electric voltage, material composition and slenderness ratio on the size-dependent buckling characteristics of the FG piezoelectric nanobeams. It is found that for all values of elastic foundation parameters nonlocality and power-law exponent yields in reduction on both rigidity of the nanobeam structure and buckling loads. But with the rise in magnitude of Winkler or Pasternak constants the rigidity of the FGP nanobeam as well as the buckling load results increase. Moreover, it is deduced that the electric voltage value has an important influence on the buckling loads of FGP nanobeams. A change in the external electric voltage from a negative value to a positive value yields reduction in the buckling loads and bending rigidity.

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JJMIE

Volume 11 Number 2, April. 2017
ISSN 1995-6665
Pages 97 -103

Jordan Journal of Mechanical and Industrial Engineering

Efficiency Assessment in Emergency Department Using Lean Thinking Approach

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Received Jan., 20, 2017 Accepted May, 10, 2017

Abstract

Lean thinking approach plays a vital role in reducing waste and enhancing productivity in production environment and service setups. Lean thinking approach may be employed in cutting down the patients' waiting time in emergency departments and hospitals. Also, lean thinking approach may be used in testing the usage of the existing facilities planned and constructed for customers' use. In the present study, lean manufacturing approach has been used to test the usage of the emergency department's services. Four vital sections of the hospital emergency department viz. Male Treatment Room (MTR), Female Treatment Room (FTR), Male Observation Room (MOR), and Female Observation Room (FOR), are studied in terms of bed occupancy. Using the concept of takt time, an individual department efficiency and relative efficiency have been calculated to find the waiting time of customers intending to use the emergency services. A case of a governmental, non-profit and teaching hospital in the southern region of Saudi Arabia has been used to present the methodology based on lean manufacturing approach systematically. In conclusion, the present study revealed that extra equipped beds have been used in these four rooms in the emergency department that can be allocated to the other crowding witnessed rooms of the same department.

Keywords: *Efficiency, lean thinking, emergency department, length of stay, cycle time, takt time, waiting time, Saudi Arabia*.

1. Introduction

Emergency Department (ED) plays a vital role in risk management of a mankind. In the present age, there is a growing risk of sudden epidemic and increased accident rate that put burden on ED. Natural or man-made disasters, accidents, sudden surge of infectious virus borne diseases, etc. are the major reasons for crowding the ED. According to Saudi Arabia statistics, a car accident happens every second and 17 people are being killed in crashes every day on an average [1].

Nowadays Emergency Departments (EDs) face major problems and some of them are very critical, such as overcrowding of patients, deterioration of quality of care, patients leaving without being seen, ambulance diversion due to crowding in ED, shortages of staff, cost containment, patient safety, etc. [2, 3]. The emergency system has become increasingly crowded during the past decade and hence the patients' waiting times are prolonged, which in turn has a detrimental effect on the patients' morbidity and mortality [4, 5, 6] and staff performance [7]. In addition to that, increased waiting time to discharge medical aids to the patient brought in and length of stay are the major worries to a common man. Therefore, emergency departments crowding in a large number of countries all over the world is started to be considered as a major threat and common health concern. Unfortunately, this crowding problem in ED continues to be more badly and hence threatens the quality and efficiency of the delivered healthcare services.

Lean thinking (also known as lean manufacturing, Toyota Production System (TPS), or simply lean) is a continuous quality improvement technique and management philosophy which is originated within Toyota corporation boundaries and thereafter widely applied across many fields, such as healthcare systems, manufacturing systems, and service facilities. Lean thinking methodology focuses on continual process improvement, worker partnership, problem solving, and the elimination of seven types of waste that defined by Taiicho Ohno [8-12]. Lean thinking has already been widely utilized across many healthcare facilities and organization in order to eliminate unnecessary waste, improve patients flow, reduce waiting times, maximize value to the customer, improve quality and increase efficiency [13-19]. Consequently, it is a tool of quality improvement that can considerably enhance efficiency and service quality [20, 21].

Dart [16] stated that lean thinking principles have gone far in the last decade and applied in manufacturing, production and service organization for thousands of times and the application of this approach in emergency departments will not be an exception. As a result, lean thinking can be considered as a different method for achieving efficiency in the ED. Therefore, lean thinking has been applied in healthcare systems and emergency departments for reducing waste and improving patient flow. However, the application of lean thinking to measure and improve the efficiency in ED did not receive enough attention in research and, hence, the relationship between lean thinking and efficiency enhancement in ED is still vague and requires a thorough study and investigation.

Efficiency is a significant factor for the estimation of both system and resources performance in the emergency department. It is defined by the Institute of Medicine (IOM) as "avoiding waste, including waste of equipment, supplies, ideas, and energy" [22-24] and it is indicated to be as one of six main objectives for enhancing the twenty first century healthcare systems in United States [25]. The IOM report mentioned that the healthcare systems should be efficient, effective, safe, timely, patient – centered and equitable in order to be of high quality [26, 27]. Also; the Institute of Medicine defined the aims of efficiency for quality improvement as "resources are used to get the best value for the money spent." The IOM and the National Academy of Engineering (NAE) published a joint report indicating that healthcare systems in US losing 30 to 40 cents of every single dollar spent due to inefficiency and waste [28].

Expanding the EDs capacity is not enough to tackle the crowding issue or improve the quality and efficiency of the provided services [29] yet the EDs should enhance patient flow, resources and processes efficiency. Therefore, establishing efficient and effective strategies to increase the emergency departments' efficiency should receive higher priority from hospitals management. Abdelhadi and Shakoor [30] reported that improving efficiency within the healthcare system or emergency department is the key component for increasing quality and sustainability of the provided services to patients. Also, reducing wastes and enhancing service efficiency of the process leads to a significant decrease in the operating cost [31]. Thus, several researchers and scientists paid an attention to efficiency issue in healthcare systems and deeply investigated the factors that affect this problem and proposed suggestions for improving efficiencies in healthcare facilities and organization [32, 33].

Obviously, the research effort on healthcare efficiency and particularly attempts to improve efficiency in emergency departments is still in the infancy stage. Different and inconsistent criterions for estimating efficiency in the emergency departments were investigated and tested, such as patient Length of Stay (LOS) [34-36] ratio-based measures [37] frontier techniques [38], etc. This inconsistency in standards for measuring the efficiency in EDs have stimulated various agencies to support the efforts for the development of new techniques to measure the EDs efficiency

Thus, looking at the ample potential and opportunities of lean implementations in services, the present research has been carried out to use lean methodology in emergency department of a governmental hospital in the southern region of Saudi Arabia. The present study is aimed at using beds efficiency in various rooms of ED as a measure of ED efficiency because a significant number of free beds or unavailable beds for most of the time may give a clear image about the ED department effectiveness. Hence, using lean thinking approach, the efficiency of resources (equipped beds) in various rooms of ED will be assessed so that a useful comparison and improvement can be suggested if needed. Also, it has been noticed that inventory waste in terms of extra equipped beds in various rooms of the EDs can be reduced by applying lean thinking. Thus, the present work attempts to bridge this gap.

2. Methodology

2.1. Study Design and Setting

This is a retrospective cohort study carried out in ED of a governmental, teaching and general hospital providing medical care to the residents of Abha region in the southern part of Saudi Arabia with a population of more than 350 000. The medical services provided in the ED during 24 hours per day and 7 days per week. The emergency department consist of the following rooms: Male Treatment Room (MTR), Female Treatment Room (FTR), Male Observation Room (MOR), Female Observation Room (FOR), Pediatric treatment room, pediatric observation room, Urgent (cold cases) room, and the Rapid Response medical and Rapid Response trauma room (RR – medical and RR - trauma). In the present research, 38 beds are assigned out of 67 beds for the rooms under study. Out of 38 beds, 20 beds are allocated equally for MTR, FTR whereas 18 beds allocated equally for MOR, FOR.

The admitted cases to the rooms under study were adult patients of ages greater than 12 years old who arrived at the ED between November 1, 2013 and October 31, 2014 and the data were collected from the ED database.

The hospital management noticed that some rooms in the ED are suffering from patients overcrowding and ambulance diversion; whereas, others have a portion of beds that are not been utilized for most of the time.

2.2. Data Collection and Study Outcome

The nurses at the ED reception desk record the required information for every patient arrives at the ED. The information includes personal details, arrival time, triage category, entry date and time to room, room classification and departure time. This information is saved in the hospital data collection database and the required data for the present study were retrieved from this database.

The three outcomes that determined every day are the number of occupied beds by patients, the maximum number of beds occupied simultaneously in every room of the four different rooms and the total time a bed reserved by patients. The estimated period of the occupied bed by a patient was specified from the time a bed assigned to the patient till the time of departure from the ED. The total available times for beds in each room were calculated during a one year study period and all time units were in minutes.

2.3. Results

During the study period (November 1, 2013 till October 31, 2014), 17149 patients were admitted to the four rooms under study, as shown in Table 1. All patients admitted to the four rooms were included in the study and there were no exclusion criteria. The following data were extracted from the database: date and time of arrival to the ED, date and time of entry to the room, age, sex, the date and time of departure from ED.

The specified time that the patient reserves the bed from the moment he or she admitted to the room until discharged from the emergency department is defined as the length of stay (LOS). In the present study, to compare the efficiencies of various rooms in the ED, actual data for the length of stay are required. Therefore, the collected data for MTR, FTR, MOR, and FOR are tabulated in Table 1.

Table 1: Summary of total number of patients admitted and the patients LOS time for MTR, FTR, MOR, and FOR in ED of emergency department

ED Rooms	Total No of Patients	LOS time in bed in minutes	Available Time in minutes
MTR	8274	2645060	5256000*
FTR	5816	2178826	5256000*
MOR	1512	897556	4730400**
FOR	1547	838482	4730400**

*Available time (Monday to Sunday for 24 hours/ day) =10*24*60*365=5256000 min

**Available time (Monday to Sunday for 24 hours/ day) =9*24*60*365=4730400 min

3. Data Analysis

Cycle time and takt time are the important process analysis parameters required in determining the system efficiency and effective service rate. Cycle time is how long it should take to serve a patient in ED and it includes value added activities and non-value added activities thus warrants a careful attention to achieve the desired service rate. In the ideal situation, cycle time equals the takt time. Thus, service doesn't warrant any additional attention.

In the present study, takt time is selected as a quantitative tool to measure the efficiency of the ED. Various rooms of ED, like MTR, FTR, MOR and FOR, are considered for the present study. Takt time in ED has been calculated by dividing operational time per period by required number of patients to be treated per period.

$$\text{Takt time} = \frac{\textit{Operational time per period}}{\textit{Required number of patients to be treated per period}} \quad (1)$$

Where:

Operational time =
Total available service time – Breaks (2)

$$\text{Required service rate} = \text{Number of patients to be served} = \frac{\text{Services provided to total patients}}{\text{Working periods per period}} \quad (3)$$

Takt time can be used for all units in the value stream to adjust served patients to actual demand in order to serve more patients during crowding.

Cycle Time and Takt Time Comparison

Based on the actual data collected from the hospital for four rooms of ED, i.e., MTR, FTR, MOR, and FOR rooms, the actual available time/year was calculated for each room using the available facilities as shown in Table 1. Later on cycle time and takt time were calculated for each room in order to compare the efficiency of each room with others. Cycle time is calculated as the ratio of the total actual time it takes the patients to get served to the total number of patients in a time period whereas the takt time is calculated as the ratio of total available time to serve to the total number of patients in a time period. The cycle time and takt time thus obtained are further used to calculate the efficiency of each room. The efficiency of the different rooms in the emergency department will be estimated on the bases of a ratio based measure.

MTR vs. FTR

- For the MTR:

Cycle time = $\frac{2645060}{8274}$ = 319.68 min / patient

Takt time = $\frac{5256000}{8274}$ = 635.24 min / patient

Efficiency = $E_{MTR} = \frac{\text{Cycle time}}{\text{Takt time}} = \frac{319.68 \text{ min./ patient}}{635.24 \text{ min./ patient}} = 0.50$, i.e., 50.00%

- For the FTR:

Cycle time = $\frac{2178826}{5816}$ = 374.63 min. / patient

Takt time = $\frac{5256000}{5816}$ = 903.7 min. / patient

Efficiency = $E_{FTR} = \frac{\text{Cycle time}}{\text{Takt time}} = \frac{374.63 \text{ min. / patient}}{903.7 \text{ min./ patient}} = 0.42$, i.e., 42.00%

Cycle time and takt time for MTR and FTR are carried out and compared in Table 2. The cycle time, takt time and calculated efficiency are represented for easy understanding in Figure 1 and Figure 2.

Table 2: Cycle Time, takt time and efficiency of MTR and FTR of ED

Description	MTR	FTR
Cycle time	$= \frac{2645060}{8274}$ = 319.68 min / patient	$= \frac{2178826}{5816}$ = 374.63 min. / patient
Takt Time	$= \frac{5256000}{8274}$ = 635.24 min / patient	$= \frac{5256000}{5816}$ = 903.7 min. / patient
Efficiency	$\frac{319.68 \text{ min./ patient}}{635.24 \text{ min./ patient}}$ = 0.50 i.e. 50.00%	$\frac{374.63 \text{ min. / patient}}{903.7 \text{ min./ patient}}$ = 0.42 i.e. 42%

Cycle time and takt time for MOR and FOR are calculated and compared as shown in Table 3. The results of cycle time, takt time and calculated efficiency are graphically represented for easy understanding in Figure 3 and Figure 4.

MOR vs. FOR

- For the MOR:

Cycle time = $\frac{897556}{1512}$ = 593.62 min. / patient

Takt time = $\frac{4730400}{1512}$ = 3128.57 min. / patient

EMOR=$\frac{\text{Cycle time}}{\text{Takt time}}$= $\frac{593.62 \text{ min./ patient}}{3128.57 \text{ min./ patient}}$ = 0.19, i.e., 19.00%

- For the FOR:

Cycle time = $\frac{838482}{1547}$ = 542.0 min / patient

Takt time = $\frac{4730400}{1547}$ = 3057.8 min / patient

EFOR=$\frac{\text{Cycle time}}{\text{Takt time}}$= $\frac{542.0 \text{ min./ patient}}{3057.8 \text{ min./ patient}}$ = 0.177, i.e., 17.7%

The various results obtained for MOR, and FOR are tabulated in Table 3.

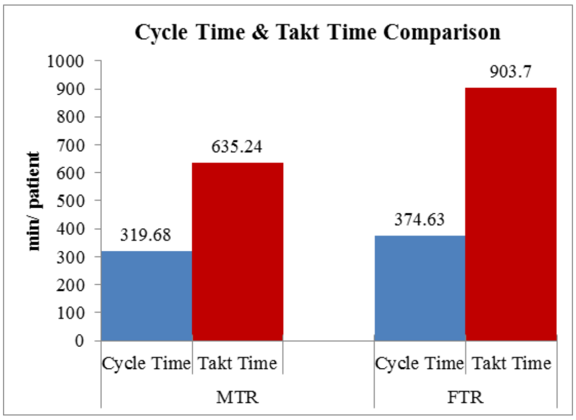

Figure 1: Comparing cycle time and takt time of MTR and FTR of emergency department

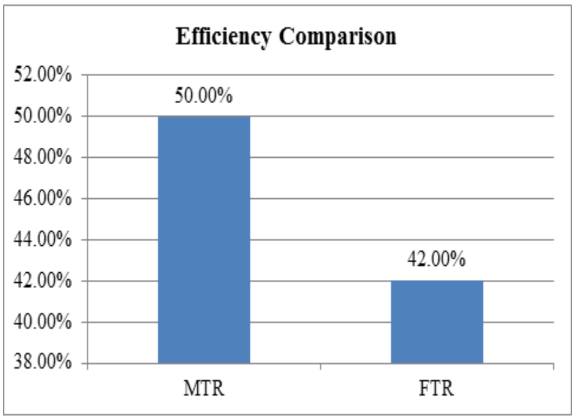

Figure 2: Comparing efficiency of MTR and FTR of emergency department

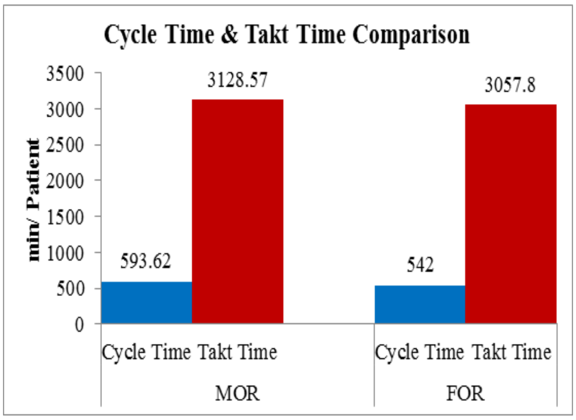

Figure 3: Comparing cycle time and takt time of MOR and FOR of ED

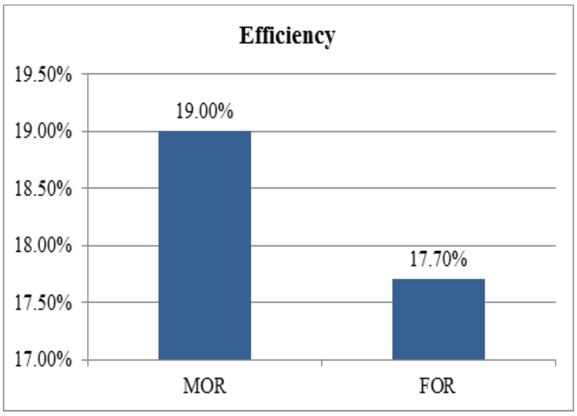

Figure 4: Comparing efficiency of MOR and FOR of ED

Table 3: Cycle time, takt time and efficiency of MOR and FOR of ED

Description	MOR	FOR
Cycle time	= $\frac{897556}{1512}$ = 593.62 min. / patient	= $\frac{838482}{1547}$ = 542.0 min / patient
Takt Time	= $\frac{4730400}{1512}$ = 3128.57 min. / patient	= $\frac{4730400}{1547}$ = 3057.8 min / patient
Efficiency	$\frac{593.62 \text{ min./ patient}}{3128.57 \text{ min./ patient}}$ = 0.19 i.e. 19.00%	$\frac{542.0 \text{ min./ patient}}{3057.8 \text{ min./ patient}}$= 0.177 i.e. 17.7%

The efficiency of the four rooms of ED are compared and depicted graphically in Figure 5 for clear understanding.

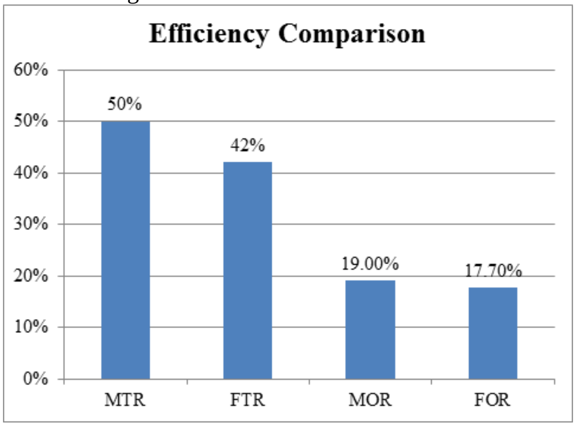

Figure 5: Comparing efficiency of MTR, FTR, MOR and FOR of emergency department

A concept of relative efficiency $RE_{X/Y}$ is used to compare the efficiency between the two rooms *X* and *Y* as follows:

$$RE_{X/Y} = \frac{E_X}{E_Y}$$

Thus, the $RE_{MTR/FTR}$ i.e. relative efficiency between MTR and FTR can be calculated as follows:

$$RE_{MTR/FTR} = \frac{E_{MTR}}{E_{FTR}} = \frac{0.50}{0.42} = 1.19,$$

This figure implies that MTR is 1.19 times more efficient than the FTR. Likewise, all the relative efficiency among MTR, FTR, MOR and FOR were calculated and tabulated in Table 4.

Table 4: The relative efficiency among MTR, FTR, MOR, and FOR of emergency department

	MTR	FTR	MOR	FOR
MTR	-	1.19	2.63	2.83
FTR	-	-	2.21	2.37
MOR	-	-	-	1.07
FOR	-	-	-	-

4. Discussion and Conclusions

Cycle time deals with the time needed to complete the operations whereas the takt time deals with the time needed to complete the operations with respect to patients' demand and the available time. In the present study, cycle time and takt time of four rooms of ED, i.e., MTR, FTR, MOR and FOR were calculated and compared for meaningful inferences as follows:

- Case of MTR

The cycle time < takt time (i.e., 319.68 < 635.24), cycle time is 319.68 minutes, whereas takt time is 635.24 minutes. Therefore, it is obvious in this case that there is an extra equipped beds used in the MTR room which is a type of inventory waste as defined in lean thinking and doesn't add a value to the patients. Whereas the service is smooth and considered to be efficient when cycle time = takt time which is the ideal case.

In this case, MTR's inefficiency in managing patient in the ED has been surfaced out. MTR has been underutilizing the capacity to serve the patients in more efficient ways. The efficiency of MTR (E_{MTR}) is calculated as ratio of cycle time to takt time, and found to be E_{MTR}= 0.50 i.e 50%. The efficiency so obtained may also be compared with ideal case. It is evident from the calculation that wasted resources (extra beds) are used in the MTR room which incurs enormous costs and reduces the department efficiency. Hence, this waste requires a management action to eliminate it by cutting down the number of beds to improve the efficiency, quality of provided services, and reduce cost. Eliminated beds can be utilized in other rooms were overcrowding and ambulance diversion problems exist.

- Case of FTR

The cycle time < takt time (i.e., 374.63 < 903.7), cycle time is 374.63 minutes, whereas takt time is 903.7 minutes. In this case, the FTR's is also having a problem in managing the patients. FTR has been underutilizing the capacity to serve the patients in more efficient ways. The efficiency of FTR (E_{FTR}) has been found as E_{FTR}= 0.42 i.e. 42%. From the results, it can be said that wasted resources are used in the FTR room which requires a management action to eliminate it for improving the efficiency, quality, and cost reduction purposes.

- Case of MOR

The cycle time < takt time (i.e., 593.62 < 3128.57), cycle time is 593.62 minutes, whereas takt time is 3128.57 minutes. In this case, the MOR's is also having enormous problems in managing the patients' crowd in the ED. The efficiency of MOR (E_{MOR}) has been found as E_{MOR}= 0.19, i.e., 19%. Therefore, more inventory waste (extra beds) exists in the MOR room according to lean thinking principles.

- Case of FOR

The cycle time < takt time (i.e., 542.0 < 3057.80), cycle time is 542.0 minutes, whereas takt time is 3057.80 minutes. In this case, the FOR's is also having a problem in managing the patients rushing into the ED. The efficiency of FOR (E_{FOR}) has been found as E_{FOR}= 0.177, i.e., 17.7% and it is obvious that more inventory waste exists in this room.

The MTR, FTR, MOR and FOR rooms of the emergency department are underutilizing the capacity to serve the patients, thus warrants the implementation of lean principles so that rooms can operate in an efficient ways. From the above results, it is evident that efficiency in FOR and MOR rooms is less hence non effective time has to be curtailed. In case of MTR and FTR rooms, the efficiency obtained are reasonably good but still can be improved by reducing the number of beds thus it can be assumed that the patients' services are managed effectively. From calculation, the following relations can be established:

$$E_{MTR} > E_{FTR} > E_{MOR} > E_{FOR}\ ,$$

i.e., 50.00% > 42.00% > 19.00% > 17.70%

Looking at the efficiency calculations, it has been observed that efficiencies of MOR and FOR are 50% less that MTR and FTR, respectively. Hence, there is a crowding witnessed at two rooms of ED i.e. Rapid Response – medical (RR – medical) and Rapid Response –

trauma (RR – trauma). Owing to this excess crowding, there are many ambulance diversions taking place to private hospitals. In order to reduce ambulance diversions to private hospitals, ED management should implement lean thinking principles to increase the efficiency of MOR and FOR at par with MTR and FTR, respectively. In some cases, management can transfer number of beds from these rooms to RR – medical and RR – trauma room in the ED. Also, hospital management may go ahead to redesign the layout of the emergency department in order to accommodate the beds transfer.

4.1. Forecasting Analysis and Efficiency Improvement

A forecasting analysis has been done using the artificial neural network tool to determine the maximum number of occupied beds simultaneously in each room. It revealed that for the next three years, there will be a demand of 6, 5, 3, and 3 beds for MTR, FTR, MOR and FOR, respectively. Consequently, on the bases of these figures, an improvement strategy is suggested to reduce the number of beds in the rooms under study as 14 beds are allocated equally for MTR, FTR whereas 10 beds allocated equally for MOR, and FOR. This reduction in the number of beds will reduce the inventory waste and improve the efficiency by 21.6%, 17.8%, 15.2%, and 14.2% for MTR, FTR, MOR, and FOR, respectively. Figure 6 and Figure 7 represent the efficiency improvement versus the number of beds in the room under study.

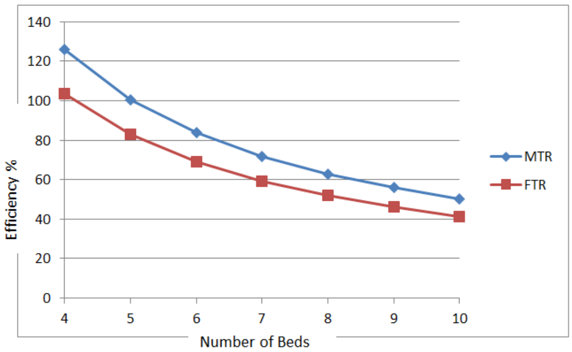

Figure 6: Efficiency improvement for MTR and FTR rooms

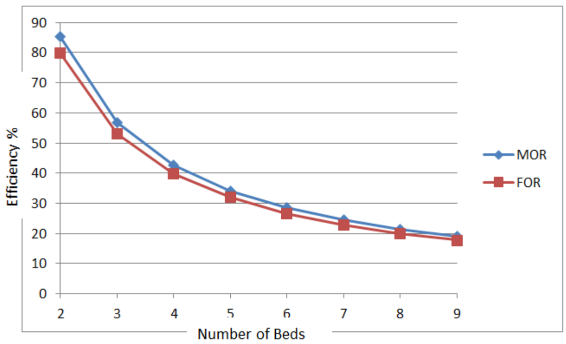

Figure 7: Efficiency improvement for MOR and FOR rooms

4.2. Managerial Implications and Future Research Directions

Using lean practices, the efficiency of a room can be measured and may be compared with other rooms to take precautionary measures to stream line patients' flow and services of the department. Also, applying lean practices, waste and waiting time of the patients can be curtailed and more effective services may be offered to needy patients in EDs. Health Maintenance Organizations (HMO) managers need to re-devise their strategies to incorporate lean practices in every room of health care system so that rapid and effective improvement can be made in the system. Many researchers observed in their studies that patient care usually improved after implementation of lean principles in health care services [15]. Also, it has been observed that many EDs have reported decreases in LOS, waiting times, and proportion of patients leaving the ED without being seen. Moreover, lean manufacturing principles can reduce waste and improve the patients' flow through the ED, resulting in greater patient satisfaction along with reduced time spent by the patient in the ED [39].

The lean approach may be applied to benchmark each and every room of the ED. It may also be applied to benchmark each service being served in every room so as to compare at global level. The present relative efficiency approach may be used to determine the number of beds, doctors, nurses and medical instruments in ED. The present approach may also be used to forecast the demand and supply rate of medical hospitals to make the service available to curb accidental death rate. A Decision Support System (DSS) may be developed to help HMO managers in critical decision making in different scenarios with increased or decreased strength of patients. Using laser aided digital camera, the patients rushing into the ED may be gauged well in time and system goes on updating and calculating the change in takt time and available time. Manager may get help from system about possible increase or decrease of medical services to offer. In such cases, manager will be well informed and more comfortable in managerial decision making.

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JJMIE

Volume 11 Number 2, April. 2017
ISSN 1995-6665
Pages 105 -112

Jordan Journal of Mechanical and Industrial Engineering

Manufacturing Flexibility and its Effect on System Performance

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Received Jan. 15, 2016 Accepted Dec. 20, 2016

Abstract

In present time, manufacturing industries are facing a very competitive, unpredictable, and ever changing environment, with growing complexity and high levels of customization. In order to achieve the customer satisfaction without sacrificing profitability, one hand industry leaders are trying to invent and adopt newer technologies and on the other hand, top management of industry requires an assurance of early return on their investment from its technical people /managers prior to actual investment in any new technology. Flexibility is probably among the most sought after manufacturing technologies. To address the issue, a prior study of the effect of different flexibility levels on manufacturing process is required. In the present paper an attempt has been made to understand the various flexibility types and their effect on the performance of a Manufacturing System (MS). It is observed that beyond a certain level of flexibility manufacturing system performance starts deterioting. A theoretical frame work for manufacturing system, factors affecting its performance & Manufacturing Flexibility (MF) is laid down. Further, an effort has also been made to present simple probable measure of various flexibility types. Towards the end with the arrangement of various flexibility dimensions in different categories on a flexibility pyramid, the concept of flexibility pyramid is proposed. Some further probable research areas are also identified.

Keywords: *Manufacturing Flexibility, Types, Measures, Flexibility Pyramid, Manufacturing System Framework.*

1. Introduction

In present dynamic and ever-changing market scenario, uncertainty is one of main characteristics. Large product variety, and shorted product life cycle are the result of technological advancement which further leads to more demanding customers with uncertainty in demands [1]. Thus, poses challenges on the manufacturing firms.

In simple words, Manufacturing System (MS) transforms raw material into desired shape and size consistently and economically. There are number of unexpected events, like fluctuating demands, machine break down, government regulations, competitor's action, consumer's choice, absenteeism, etc., making this transformation process more complex [2]. These disturbances either originated within system boundary or outside system boundary, invariably affect the overall performance of any MS. The illustrative framework for the factors affecting the performance of a MS envisioned in figure 1.

To address these unexpected disturbances, the MS essentially needs to be under the umbrella of MF. That might be one of the reasons for the concept of MF (or flexibility, both the terms are invariably used in the present paper), being among the key considerations in the design, development, operation, and management [3] of a manufacturing system. A wide range of growing literature is available for definition and dimensions of manufacturing flexibility; however limited literature is available on the measures of MF. The present paper, on one hand, aims towards the study of the effect of various flexibility types on the performance of a MS, and, on the other, it develops a framework for a MS, factors affecting its performance, and flexibility. The various MF types are arranged at different levels of a flexibility pyramid. The organization of the rest of the present paper is as follows: MF, its various types, their definition and measures are discussed in section 2. Review of relevant literature; the point of view of effect of manufacturing flexibility is grouped in two subsections according to simulation and empirical work in section 3. A frame work for manufacturing system and flexibility as well as the concept of flexibility pyramid is proposed in section 4. Conclusions drawn and scope of future work are given in section 5.

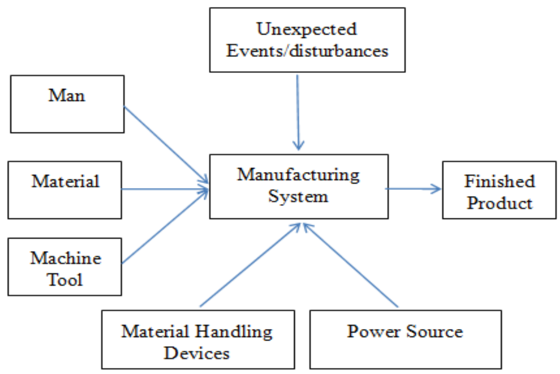

Figure 1. Framework for manufacturing system and factors affecting its performance

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2. Manufacturing Flexibility (MF)

Even though a number of authors have exerted much effort to capture the essence of flexibility and formulated number of definitions (for more details refer to [2-9]), there is a lack of general consensus on the definitions of flexibility [10]. Shewchuk & Moodie [10] found more than 70 terms on flexibility (types and measures) in the literature. Existence of at least 50 terms for the various types of MF is reported by Sethi and Sethi, in their popular survey of relevant literature [3]. Flexibility is a complex, multidimensional, and hard-to capture concept. In many cases several terms refer to the same flexibility type. Imprecise and conflicting definitions for flexibility types/ dimensions are there, even for identical terms [5]. A systematic review of vast literature available on manufacturing flexibility is recently published by Marta Pérez Pérez *et al.* [11]. Flexibility terms are studied from hierarchical and systematic perspectives. Wide terminological and conceptual ambiguity associated with the manufacturing flexibility has been addressed [11].

Here, flexibility is considered as the ability to develop and select the alternatives for a particular situation. In context of manufacturing, "*ability of a manufacturing system to develop and select alternatives for a particular manufacturing situation is known as MF"*. Alternatives may be created and selected in various dimensions under a number of situations of a manufacturing system; hence MF may have several different types/ dimensions/ forms. Ramasesh and Jaykumar [12] rightly remarkd that MF can be in number of different forms, e.g. machine, material, material handling, routing, operation, process, product, program, volume, expansion, labour, etc.

2.1. Flexibility Types and Measures

Flexibility is crucial factor for any MS. If properly utilized, it has a positive effect on the performance of a MS [13]. A number of categories and types of MF can be found in the literature. In 1984, Browne *et al.* [14] identified eight dimensions of MF, while in 1990; Sethi and Sethi [3] proposed the widely accepted concept of eleven flexibility types. These eleven types of flexibilities have been segregated into three categories, namely basic, system, and aggregate. Machine, operation, and material handling flexibilities are categorized as component or basic flexibilities. Expansion, process, product, routing, volume, flexibilities are kept in the system flexibility group. Lastly Market, program, and production flexibilities are made the category of aggregate flexibilities [2]. Later, Vokurka and O'Leary-Kelly [15] proposed four more types of flexibility, namely automation, new design, delivery, and labour. The definition for each of the fifteen flexibility dimensions (at least there is a broad consensus on these) adapted from [2-3, 14-21], and tabulated in Table 1. Though, it is very difficult to measure flexibility type directly, a fuzzy based mathematical framework to measure/quantify nine flexibility types and overall flexibility is developed in [21]. A complex mathematics delays the decision process, to keep it simple, the handy measure of all flexibility types are presented in table 1. Recently Kumar and Sharma [2], arranged ten flexibility types at different levels at which they are performed. Machine, material, and labor are placed at the level of individual/resource. Process, operation, and routing flexibilities are functions at the level of shop floor. Product, volume, production, and expansion flexibilities are performed at plant level. It is also observed independent variables machine, material handling, and labor flexibilities are linked to dependent variables, namely production, volume, and product flexibilities through linked variables, namely operation, routing, process, and expansion flexibilities.

3. Literature Review

In the underwritten lines, a review, of the literature pertaining to effect of flexibility on the performance of a MS is carried out and presented in two categories, according to the approaches of work, viz Simulation & modeling, and Empirical.

3.1. Review of Simulation and Modeling Work on Effect of Flexibility Types on System's Performance

In a review of effect of flexibility on manufacturing performance, it is observed that Susumu Morito *et al.* [23] analyzed a real life Flexible Manufacturing System (FMS), using discrete event simulation, and found that just having two or three alternative machines, would greatly enhance both the flexibility and performance of the MS. Contributions towards flexibility and performance, from more than three alternative machines would be dismal. Morito *et al*. [23] noticed that, on one the hand, make-span performance is not affected by scheduling priorities, while, on the other hand, a carefully crafted machine assignment would be crucial to attain short make-span. The findings are further strengthened by Chan [24] by the use of the Taguchi's experimental design framework with simulation techniques (ANOVA) based methodology. In most situations optimum performance is observed at routing flexibility level 1 or 2. Deterioration is system performance starts beyond this flexibility level. This suggests that increase in routing flexibility and improvement of system performance could not go together endlessly. Optimal pallet requirement, routing, and sequencing rules for hypothetical FMS were also determined by Chan, [24]. The similar results are obtained by Chauhan [25], in his study of a hypothetical FMS with ARENA simulator. He observed that beyond a suitable flexibility, and pallet level, system performance starts deteriorating, as judged by the make-span measure of performance. Continuous reduction in make-span time with the increase in routing flexibility is observed at a fixed level of delay time. When routing flexibility is further increased, the variability in make-span time due to delay time reduces [25]. Albino & Garavelli [26] by their simulation study pointed that, with the decrease in resource dependability, productivity can be effectively increased by the use of routing flexibility, particularly in the limited flexibility configuration.

Mountaz Khouja [27] reported if a system is more volume flexible, optimal production lot size will be higher; in turn, the optimal production rate would be lower. For MS having volume flexibility, the optimal production rate is smaller than the production rate required to minimize per unit production cost.

Table 1. Definitions of fifteen flexibility types / dimensions and their respective measures

S. No.	Flexibility	Definition	Measure	Remarks
1	Machine	Ability of machine to perform a range of operations without incurring any major setup	Average of different number of operations could be performed on a machine without any major setup change.	Measure in terms of time required to change tool/ set up are also observed in literature [17,21]
2	Process	Ability of system of producing variety parts without incurring any major setup	Number of different part types could be processed simultaneously.	Possibly using different material
3	Operations	Ability to produce a component / product by alternative processes or ways	Average number of alternate process orders / ways for each part type, which can be accommodated.	Without any effect on shape and size of final product
4	Product	System's ability to substitute /replace or add new part(s) for existing part	Number of substitute products could be produced quickly and economically.	Measure in terms of requisite time in switching from one part mix to another, are also observed in literature [17].
5	Routing	System's ability to have number of alternative paths within the system, by which a part could be made	Average number of alternative path by which a part could be processed.	It indicates the robustness of the system, to accommodate and break down.
6	Volume	System's ability to operate at range of different output levels economically	Number of different output levels could be produced economically	The smallest volume for all part types for profitable operation.
7	Production	System's ability to produce a plethora of products without adding new equipment	Number of products which could be made by the system	Product range; Similar to product flexibility of [22]which enables a manufacturing system to make a variety of part types with the same equipment
8	Expansion	Ease at which capacity and capability of the system may be enhanced	Capacity and capability which could be added without any major investment.	Magnitude of the MS
9	Material Handling	Material handling system's capability of moving and positioning various parts throughout the MS	Number of simultaneous components that can be moved and positioned by the system	Measure in terms of the quantity, diversity, and transportation time of parts.
10	Program	System's capability of unattended operation for a long period of time	Period for which MS could be operated/run without attention	Fraction of period for which system could be operated without attention
11	Market	Adaptability and responsiveness to the changing market environment	Response time of system to change in market	System should be proactive towards changing market
12	Automation	Level at which flexibility is incorporated in the computerization/automation of manufacturing technologies	Measure of the stage of flexible automation within the system	Proportion of plant having flexible automation
13	New Design	System's ability of designing and introducing newer products into the market well before time	Number of new design/product can be introduced from the existing facilities	Pro-activeness of the system to changing customer taste
14	Delivery	Responsiveness of the system towards changes in delivery requests	Number of simultaneous changes in delivery requests could be accommodated successfully	Ratio of number of successfully implemented changes in delivery requests to total request for change in delivery
15	Labour	Multitasking ability of labour/ operator/human resource i.e. within the MS without sacrificing the efficiency	Average number of different tasks that could be performed by an individual human resource	Ease in inter-departmental transfer of personals

The study of Chandra *et al.* [28] reflected that under the specific scenarios, the level of total demand at profitable production rate marginally affected by the increase in product mix flexibility. Meanwhile, profitability is improved by increasing product mix flexibility for a constant total demand, most significantly for total demand exceeding the system's capacity.

The study of Horng [29] observed that with limited labour resources, mixed labor assignments directly and indirectly improves the performance within a cell. This study indicates that when more than 70% of the skills are shared by all of the operators requiring higher training costs, and system performance do not improve significantly.

Deterioration in make-span performance with an increase in decision delays is reported by Wadhwa and Bhagwat [30]. This deterioration is higher at higher levels of flexibility, i.e. higher the number of available options to choose. They further observed that interaction between flexibility and decision delays results a certain level of decision delays beyond which, the performance of the system is reduced due to their cumulative effect.

Chan [31] in his study of impact of dispatching rules, operation flexibility, and the combination of these two on the performance of a FMS, observed that performance of his FMS model improved more significantly by alteration in the dispatching rules as compared to changing the levels of operation flexibility. Increasing the operation flexibility should not be taken as the key direction for performance improvement of the FMS. Among the six dispatching rules considered in the study, the shortest remaining processing time rule is found to be the best. However, none of the six levels of operation flexibility considered, can claim to be the best among the six levels. In another study of effects of routing flexibility, sequencing flexibility, and scheduling decisions on the performance of a FMS, Joseph and Sridharan [32] observed that all the performance measures of the system is improved with the introduction of sequencing flexibility, in the absence of routing flexibility. Deterioration in system performance could be minimized by the inclusion of sequencing flexibility or routing flexibility or both. However, the diminishing rate of benefits at higher flexibility levels of each of these flexibilities is observed.

In a comparative study regarding to the influence of product, transformation, and sequencing flexibility, Wadhwa *et al.* [33] found that the influence decreases from product flexibility, to transformation flexibility, to the sequencing flexibility [8]. Baykasoglu and Ozkabir [13] reported that machine flexibility effects job shop performance more in comparison to process plan flexibility. A considerable decrease in the rate of scheduling performance improvement is also observed beyond a certain level of machine flexibility.

By giving a close observation to the findings of various researchers discussed above, it is observed that increase in flexibility levels up to a particular level, it will benefits towards performance of MS. Additional increase in flexibility beyond this particular level deteriorates the performance of manufacturing system. Combination of flexibility levels of different flexibility types may be system specific and depends on the constraints and priorities of the management. Garavelli [34] compared the system performance under three different degree of flexibility total flexibility (as in a job-shop), no flexibility (as in a cellular system with no inter cell move) and limited flexibility (a particular inter cell routing flexibility), and found that the system performance under limited flexibility is optimum, while the system performance under zero flexibility is worse. The similar results were reported by the study of the impact of different routing flexibility levels on make-span of a FMS, carried out by Ali and Wadhwa [35]. The results further strengthen by Muriel *et al.* [36] in their study which indicates that the production variability is significantly increased with the introduction of partial flexibility. Further, even allocation of demand (distributed tactical capacity allocation) to the plants, leads to better performance of the flexible system. Nagarur [37] coined a framework called producibility, with the integration of both flexibility and reliability. It is a direct measure of the ability of system to accomplish the given task(s).

3.2. Review of Empirical Work on Effect of Various Flexibility Types on the Performance of a MS

In recent years much has been written about flexibility, FMS, and Flexible factories, but the literature has been largely theoretical, a little practical work has been observed.

Vokurka and Kelly [15] reviewed the empirical studies and revealed four general areas having dominant factors influencing MF, namely organizational attributes, strategy, technology, and environmental factors. The previous models, [38-41] addressed the vital relationship between MF and environmental uncertainty, but do not address relationships involving MF, organizational attributes, business strategy, and technology. Limited relationships are addressed by these models [15]. Finally, they proposed their own framework. These all frameworks incorporate the effect of all flexibility type under a single variable "MF".

Suarez *et al.* [41] divided flexibility types into two major categories, namely, "First order" flexibilities and "lower order" flexibilities. Flexibility types segregated as first order flexibility directly affects the firm's competitive position in the market, and lower order flexibility types communicate their final effect through one of four first order (Mix, Delivery Time, New Product, and Volume) flexibility types. Some of Their major findings are as: (a) more automation leads to less flexible (b) Worker involvement, supplier relationship, flexible wage system, etc. appear to increase new-product, mix, and volume flexibility (c) Both mix and new product flexibility seem to be raised by component reusability (d) A mutual reinforcement between new-product and mix flexibility is observed, and likely to be further supported by similar other factors (e) Volume fluctuations may be reduced by Mix flexibility. Hence a theoretical reduction is "in the need of volume flexibility". In their study, Jack and Raturi [42] used empirical research methodologies to test and validate their hypotheses. They reported a positive impact of volume flexibility on performance.

In general, Hallgren and Olhager [43] observed plants having high flexibility levels performs better in all four operational performance measures, namely cost, conformance to quality standards, speedy and on-time of delivery, as compared to plants having low flexibility levels. On the front of on-time delivery, the volume flexible plants demonstrate better performance than mix flexible plants however; on other fronts the performance of multi flexibility plants is significantly higher as compared to only volume flexible plants. It is more important to have both mix and volume flexible [43]. Salvador *et al.* [44] found that mix flexibility is negatively affected by the few approaches used to increase volume flexibility and vice versa.

Findings of an empirical study, named the effect of manufacturing flexibility on export performance in China by Ogunmokun and Li, relates manufacturing flexibility to export performance, with a major implication that organizations that are not flexible in their manufacturing may be hindering the performance of their export ventures, necessary for sustaining the survival of their operations [45].

Luan *et al.* [46] in their empirical research and survey of about 381 manufacturing enterprises found that flexible manufacturing competence has positive, significant and direct impacts on firm's competitive advantage. The similar results are reported by Lee and Chen [47] in their empirical study of organizational Performance of Taiwan-listed photovoltaic companies. In 2015, a survey on competitiveness of small and medium enterprise of north India, Kaur *et al.* [48] found that labor flexibility has the highest impact on competitiveness of the firm followed by the machine flexibility and material handling flexibility. In another empirical study of a food industry, Chang [16] priorities the effect of eight flexibility types in the following order (highest first) production flexibility, product flexibility, market flexibility, labor flexibility, machine flexibility, volume flexibility, material handling flexibility, expansion flexibility. Zainol *et al.* [49] reported a good positive impact of MF on product modularity also.

In 2016, a study of relationship between Manufacturing Flexibility Competency (MFC), Innovation Capability (IC) and Operation Performance (OP) of Indonesian manufacturing firms is published and reported a positive association among the three. Further it inferred that IC mediates between MFC and OP [50].

Recently, Brettel *et al.* identified the relationships between flexibility and performance by systematically charting empirical findings from the literature and linked this development to the advancements of manufacturing schemes of industries 4 [51].

4. The Frame Work

From the above literature review, it is evident that some flexibility types have direct and significant effect on the performance of a MS. Whilst, few flexibility types are hardly make any major impact on the performance of the MS. Few flexibility types, which could affect the magnitude of impact of other flexibility types on the performance of a MS, are also observed.

4.1. Framework for Manufacturing System and Flexibility

In order to develop a theoretical frame work for manufacturing system and flexibility, flexibility is considered as a panacea to all practical problems of any manufacturing system. It is evident that Flexibility is a stronger predictor of performance in more dynamic environments [52]. The framework envisioned in figure 1 can be modified by encircling manufacturing process with the MF. As flexibility is the ability of system to deal with change, hence all changes as well as prospective changes must be handled by MF prior to affecting the MS, for the sake of pro-activeness of the system. Hence, all unexpected events can be removed as they are the by-product of other factors and parameters. Organizational attributes, strategy, and environmental factors must be added to get a fairer and complete picture. Literature [15] has the strong evidences regarding the influence of organizational attribute, strategy and environmental factors on manufacturing system performance similar to the common belief. The technological aspects may be covered by machine tool, material handling devices and skilled manpower etc. The modified frame work is depicted in figure 2.

For the simplest analysis of frame work, if the material handling system of MS can handle any component in two different ways, it could be said that MS has two units of material handling flexibility. It gives the leverage to the MS to handle a component and raw material. But if the material handling system is of the same material it can handle a component in 10 ways. Above this if the same MS has such large level of flexibility in number of flexibility types, in most of the cases, the total number of choices is the product of all such flexibility level. It makes a very large number of choices to select, selection from a large number of choices introduce delay in decision. Further a major portion of capability remains unutilized. Further IT implementation has direct and significant impact positive operations performance on Machine, Labor, Material handling and Volume flexibility dimensions Mix and Routing flexibility dimensions [53]. IT implementation could be used for enhancement of effectiveness of the system.

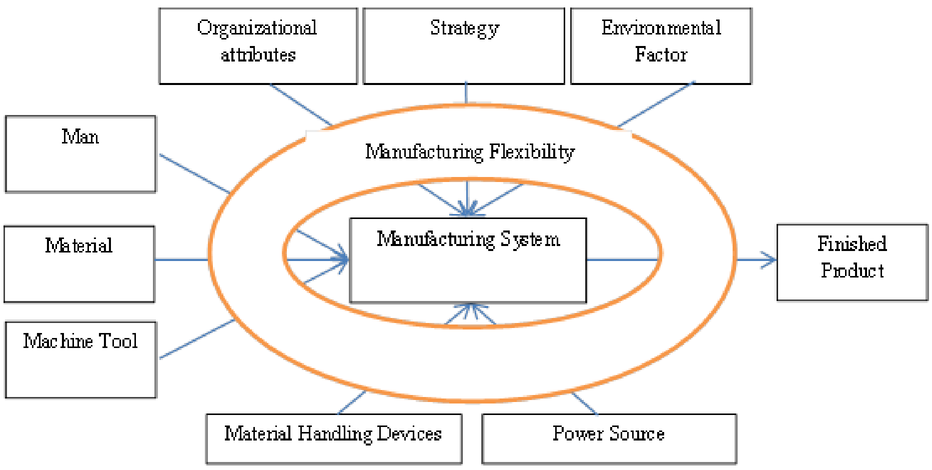

Figure 2: Framework for manufacturing system, factors affecting its performance, and Manufacturing Flexibility

4.2. Various Categories of Flexibility Types

Saurez *et al.* [41] divided flexibility types into two main orders, namely order 1 and lower orders, by using firm to market approach. In their model lower order flexibility types are wide side of funnel, i.e. firm side and first order flexibility types are narrow side of funnel, i.e. market side. Competitive position of the firm into the market is directly affected by the flexibility types grouped as Order 1 viz: Volume, New Product, Delivery, Production (Product mix), and effect of order 1 flexibility types is easily perceived by the customers. Lower Order contains all other flexibility types. Kumar and Sharma [2] divided 10 flexibility types into three levels, namely flexibility types performed at plant level, shop floor level, and individual/ resource level. Kumar and Sharma [2], further segregated these 10 flexibility types as independent variables, linkage variables, and dependent variables.

Here, four different categories of flexibility types are suggested. All 15 flexibilities types, discussed here are segregated into four different categories by a careful study of both analytical and empirical research analyzing the impact of various flexibility types on the performance of a MS available to us so far. Category 2 is kept same as order 1 of [41] because all exercise is done to retain and improve the competitive position at the market, and these four are critical for market position. Remaining flexibility types are divided into three categories (category 1, category 3, and category 4) as per the flow of firm's response towards market changes.

It is not necessary, for a certain firm, to infuse all kind of flexibility dimensions in its system to remain in competition. The flexibility types and level of each flexibility type requirement may be different for different industries. Further the optimum level of all required flexibility types may also be different from the optimum level of each other.

- Category **1:** Flexibility types for efficient adoption of customer demand and innovation, pro-activeness of the firm to adapt in the changing market scenario, generally performed by top level management not only to sustain but to capture the larger market share: new design, and market
- Category **2:** Flexibility types which directly affect the Firm's competitive position in the market: decision in taken at the plant level management: volume, product, delivery, and production (product mix)
- Category **3:** Flexibilities generally performed at shop floor personals in order to meet the plant production objectives: program, expansion, automation, operations, routing (Sequencing), and process
- Category **4:** Flexibility types which would be performed mainly at individuals in order to meet the shop floor production targets: machine flexibility, material handling, and labour (human resource).

4.3. Flexibility Pyramid

After defining the levels of flexibilities a flexibility pyramid can be developed. Flexibilities of category 1 to category 4 are positioned from apex to bottom of pyramid as illustrated in figure 3. As move from bottom to top of pyramid number of people involved decreases. In tune to [2], bottom variables are independent to other flexibility dimensions. They are most crucial for system performance. While variables are at apex of pyramid are dependent variables. These are crucial for pro-activeness of the system. Linkages variables are in middle of pyramid. Importance of flexibility type in order to response to market decreases from apex to bottom of pyramid. For manufacturing performance, importance of parameter from bottom to top decreases. Flexibility types at bottom sharply and immediate affect the manufacturing performance, while effect of flexibility types at apex are visible in long term. The effect of flexibility types at lower order may be transformed into the one of flexibility types at higher order.

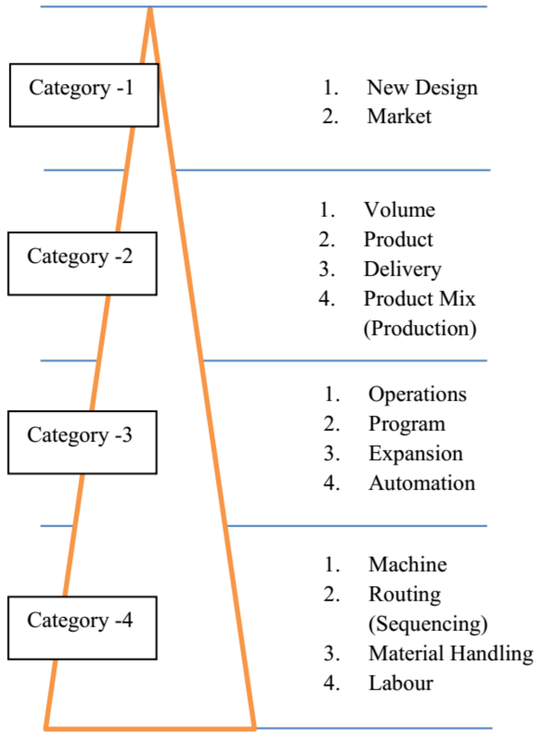

Fig. 3: Pyramid for Flexibility Types

5. Conclusion

From the above discussion it is evident that a certain degree of flexibility is not only beneficial but essential for modern manufacturing industry in present dynamic environment. Every firm has to estimate the flexibility types and its degree required for its sustainable growth. Flexibility is required at different level of organization and each one has its own importance, and most of them are inter-linked. Further flexibility pyramid would be a handy tool to make an understanding of the essence of flexibility. In spite of the development of a theoretical frame work, and flexibility pyramid, and above concluding remarks, following Observations and future scope of work might be helpful for a broader insight of the topic.

5.1. Observations

From the discussion in the article, following observations can be made:

- Major thrust area of researchers is on routing / scheduling flexibility, machine flexibility and labor flexibility, volume flexibility in order, and a little work is carried out on other types of flexibility.
- Up to a certain level of flexibility, the performance of MS increases with the rise in flexibility level
- Rise in flexibility level beyond this threshold value, deterioration in system performance starts and makes it even worse. The reason of this may be the increase in choices, as increase in choices leads to larger in decision delay.
- From empirical research, it is evident that every manufacturing unit has its different needs and requirement of flexibility type(s). That's why managers are advised to choose the required flexibility type(s) and their respective level(s) carefully.

Prior estimation of the impact a given type and level of flexibility on the performance of MS will be beneficial for both the operation and design of manufacturing systems. Every increment in any flexibility type or its level into the system adds to cost. Return on investment is one of the basic and foremost criteria for adoption of any newer technology. Rate of return method is a widely accepted powerful tool in accepting /rejecting decisions [54]. Flexibility analysis would be an effective tool for economic justification of adoption of certain flexibility types and their respective levels, and may be used tactically in finding conditions & opportunities for which flexibility can drive the maximum benefits. That is why a prior study of the effect flexibility on performance and optimum level of various flexibility types for a manufacturing system is inevitable.

5.2. Scope of Further Work

From the study the scope of further work could be identified as follows:

- Priorities the effect of various flexibility types and their respective levels separately on the MS's performance.
- Ordering of flexibility types according to their impact on manufacturing system performance.
- Knowledge management and IT implementation are also handy and vital tools to handle the change; there is also a scope of study of effect of knowledge management in combination with flexibility and reliability in manufacturing system.
- Effect of a particular flexibility type on other flexibility type(s) for a particular MS and in general too.
- Research studies are more focused towards modeling and simulation approach, a wide scope of empirical research is there.

Acknowledgments

Authors are indebted to the unknown reviewers and editor for their critical review and the pointing suggestions that enabled us to bring out the present form of the work. We are, indeed, thankful to them

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JJMIE

Volume 11 Number 2, April. 2017
ISSN 1995-6665
Pages 113 -119

Jordan Journal of Mechanical and Industrial Engineering

Assessment of Implementing Jordan's Renewable Energy Plan on the Electricity Grid

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Received July, 15, 2016 *Accepted Oct., 18, 2016*

Abstract

In the present work, the technical and economic impacts of integrating large scale renewable energy projects of wind and PV systems to the transmission grid in Jordan up to the year 2025 has been investigated. The current grid transmission system of Jordan’s electricity network has been modeled and used. Large renewable energy systems of PV and Wind proposed by the master energy plan in Jordan have been introduced to the grid. The Digital Simulation and Electrical Network Calculation (DIGSILENT) program (i.e., power analysis program) and the Wien Automatic System Planning Model (WASP) software were used to evaluate both the technical and economic impacts. It is found that until 2018 Jordan’s transmission grid will face minor overloads, while, most of transmission lines will be overloaded by 2020. The technical and economic aspects of the existence of a special transmission line (Green Corridor) from the generation site in the south to the demand locations in the center is investigated and documented. It is found that this solution is vital to the transmission grid and feasible. Moreover, it revealed that because of the dependence of renewable energy systems the LCOE by 2025 will vary only 25 % (between 100 to 125 USD/MWh) when the price of NG increases 50% (from 8 to 12 $/MMBTU) in spite of the additional cost of the "Green Corridor" of 145 M$ for grid reinforcement. Also, it is expected that with the target renewable energy projects and new conventional power plants the LCOE in 2025 will be 43 % less than that in 2014.

Keywords: *Transmission Grid, Grid Impact, Renewable Energy Systems, Green Corridor.*

1. Introduction

Jordan is one of the highest countries in the world in terms of the dependency on the foreign energy sources where is around 97% of the energy needs are imported [1]. Also energy demand in Jordan is growing rapidly due to different reasons such as high growth in population, in addition to hosting high number of refugees from neighboring countries [2]. In order to meet the high demand on electricity and to increase the local resources shares in the energy mix, the government has directed its efforts recently towards encouraging the investment in the renewable energy sector on both large and small scales. The electricity model in Jordan is based on single buyer model where all electricity from all resources is bought by National Electric Power Company (NEPCO) and then it is sold again to the distribution companies and bulk consumers directly through transmission network. The installed generation capacity in Jordan as of 2015 is 3.8 GW, around 2.6 GW through private projects and around 1.2 GW from governmental sector. The highest registered peak load is in 2015 is 3200 MW. The transmission voltages are 400 KV and 132 KV where distribution voltages are 33, 11, and 0.4 KV, the transmission lines length is around 4600 Km circuit and main substation capacity is around 12000 MVA. Furthermore, the Jordanian grid is connected to both Syrian and Egyptian networks through high voltage AC connection on 400 KV level.

The expected renewable energy projects in Jordan come from three main paths (1) direct proposal (2) bidding process, and (3) governmental projects, Jordan has set a target of 10% of the energy mix in 2020 to be produced from renewable energy resources [5]. For this purpose and to secure the supply and to diversify the energy resources in Jordan, several electricity generation projects are committed to be connected to the grid. Table 1 shows the renewable energy projects while Table 2 shows the conventional natural gas fired projects. It should be mentioned that around 70% of the Renewable Energy Systems (RES) are to be erected in the south of Jordan. This will add difficulties to evacuate the produced power to the load center in the middle of Jordan. These challenges include overloading of transmission line, high short circuit current and other challenges that will be discussed and mentioned in the present paper. Furthermore, the development of RES includes small power plants to be connected to the distribution network, the so called "dispersed generation". The effect of this generation is considered negligible for the purpose of the present study.

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Many people have worked in the field of evaluating the impact of renewable energy integration to the electrical systems [6-7]. For example, Paul *et al.* [8] presented a simple approach for comparing the economics of integrating intermittent renewable energy resources by comparing their corresponding Levelized Cost of Energy (LCOE).

The main purpose of the present work is to study the technical and economic impacts of integration large scale renewable energy projects of wind and PV systems connected to the transmission grid in Jordan. Power analysis program Digital Simulation and Electrical Network Calculation Program, DIGSILENT, along with the current system model and proposed renewable projects and WASP (Wien Automatic System Planning Model) were used

2. Analysis

For the present work, the target year is 2025 and the base year is 2016. The database of the Jordanian power system available from NEPCO is used. This database includes data for network representation in both static and dynamic analysis of the Jordanian network, representation of power systems of Egypt and Syria, in addition to the representation of the generation units and the addition of retirement plan for the generation units. This database is revised related to the latest load forecast, generation expansion plan, power exchanges with neighboring countries and new renewable power plants. The following points summarized the main assumptions for the study:

1. All target projects of RES will be integrated to the grid as proposed while the oil shale and Nuclear projects are not.
2. Two stage calculations: stage (a) power flow calculation in sound N-network condition and stage (b) network condition in case of contingency (N-1 condition). Normal (N) Conditions the basic assumptions related with N-criterion of transmission network are: the rating limits of transmission lines should be intended as maximum permanent currents; in normal operating conditions no overload of the transmission network is allowed; no generator will be above its continuous reactive capability. According to the Grid Code the performance requirement for operating voltages under Normal conditions are: 400 kV network, the admissible voltage range is between 380 kV and 420 kV (±5%); 132 kV network, the admissible voltage range is between 118.8 kV and 145.2 kV (±10%). Contingency (N-1) Conditions, N-1 primary criterion is applied to all credible scenarios. The N-1 criterion is considered to be fulfilled, when following the first loss of a circuit or a generation unit no violation of operation limits, overloads, loss of stability and uneconomic operation of generation units or load shedding occurred [9]. In N-1 steady-state conditions the voltages can be expected to deviate outside the above limits by a further +/- 5%.
3. The demand on the generation of the PV is assumed to be 70% of the total installed capacity of the PV projects, and for the wind projects is 80%.
4. The study is based on the assumption not to import power from the neighboring countries in the future. Transfer of power along the interconnections with Egypt and Syria are expected due to power wheeling. The representation of the neighboring countries is necessary for short circuit calculations. Even though it is assumed not to utilize the electrical interconnections but they have a lot of benefits to the Jordanian system like helping in balancing the frequency of the interconnected system and reduce the RE forecast error and share flexibility resources [10-12].
5. The cost of natural gas is based on three different scenarios of 8 $/MMBTU, 10 $/MMBTU, and 12 $/MMBTU in addition to the transportation fees.
6. New generation using conventional system with total efficiency of 49%.
7. Yearly growth of peak load and energy of 5% [5].
8. The tariff of both nuclear and oil shale projects as the latest announced tariffs, 0.10 $/Kwh for nuclear and 0.13 $/Kwh for oil shale.
9. The tariff for the PV projects is 0.148 $/Kwh for 2016 and 2017, 0.0705 $/Kwh thereafter. For the wind projects is 0.117 $/Kwh for 2016 and 2017, 0.1125 $/Kwh thereafter.
10. Discount rate of 7% and 2016 as the base year.

3. Results and Discussion

Loading of several key points in the grid was calculated based on both renewable energy projects and the expansions of the conventional power plants listed in Tables 1 and 2 and their connection on the grid are shown in Fig.1 and Fig. 2. Figure 1 shows the integration of the RES in the southern part while Fig. 2 shows the situation in the northern part of Jordan. From the analysis of the grid with the connection of the renewable projects, several overloading occur in the 132KV line especially in the southern area. Figure 3 shows the loading results up to 2025 in the southern part where most of the expansions and integration of renewable projects will be allocated. It is clear that several overloading in the lines exist due to high penetration of renewable energy beside that they are not in compliance with the N-1 security criterion.

Table 1. Renewable energy projects until 2025

Year	PV (MW)	Wind (MW)	Total (MW)
2016*	475	350	825
2017*	475	500	975
2018	775	500	1275
2019	875	600	1475
2020	975	700	1675
2021	1075	800	1875
2022	1175	900	2075
2023	1275	1000	2275
2024	1375	1100	2475
2025	1475	1200	2675

* Committed projects

Table 2. Proposed conventional generation projects until 2025

Proposed new projects	Proposed connection points	Capacity (MW)	YEAR
New Rehab	REHAB 400/132kv	500	2019
Al Hizam	Al Hizam 132/33	500	2021
New Aqaba	Aqaba 132/33	500	2024
Swaimah	Swaimah S/S	500	2025
Total	---	2000	---

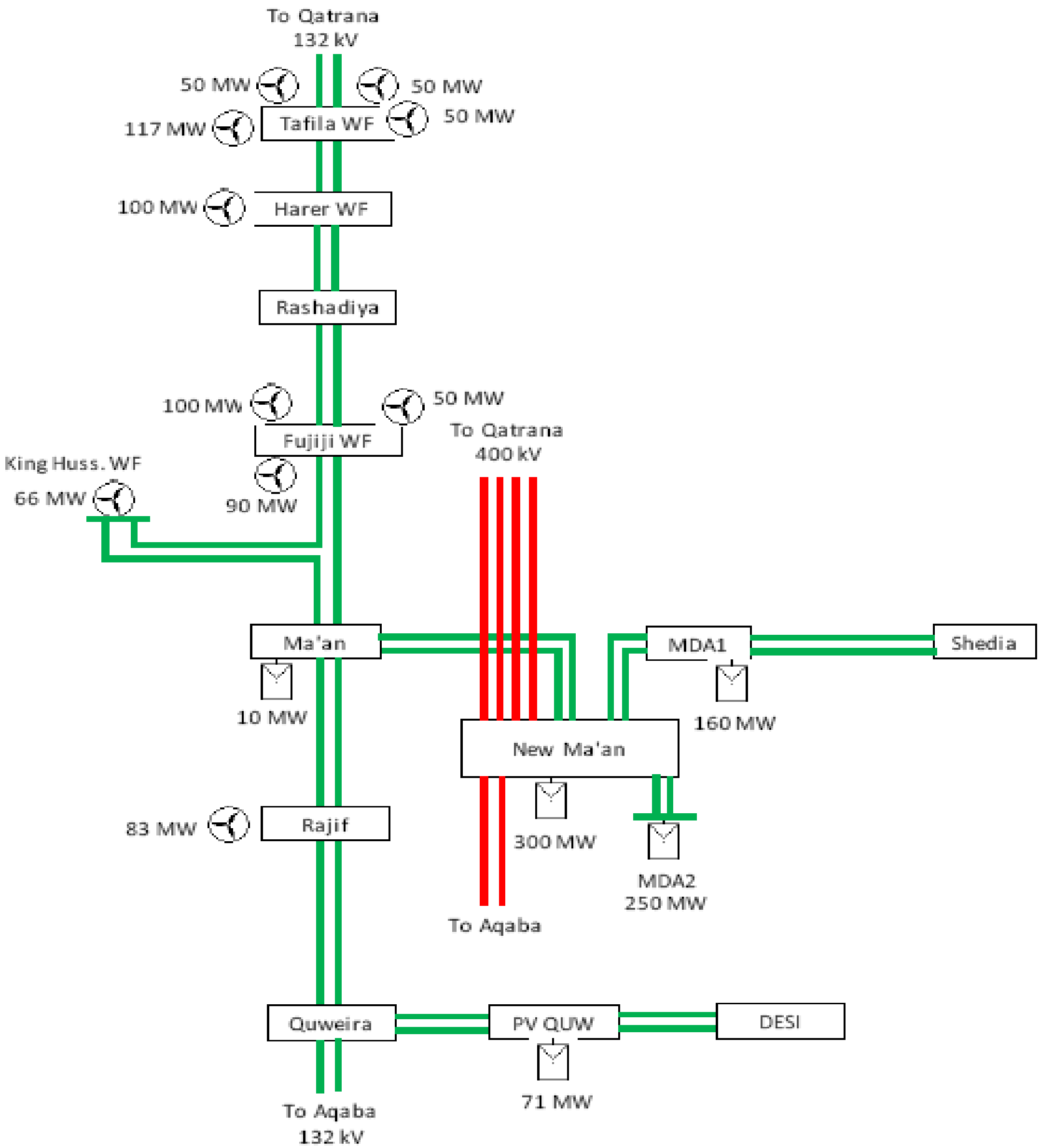


Figure 1. The connection of renewable projects in the southern area in year 2025

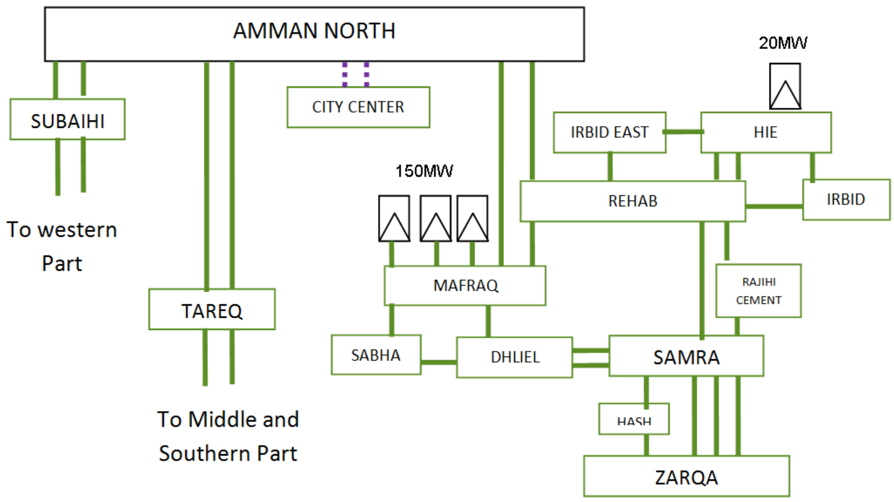


Figure 2. The connection of committed renewable projects in the northern area in year 2025

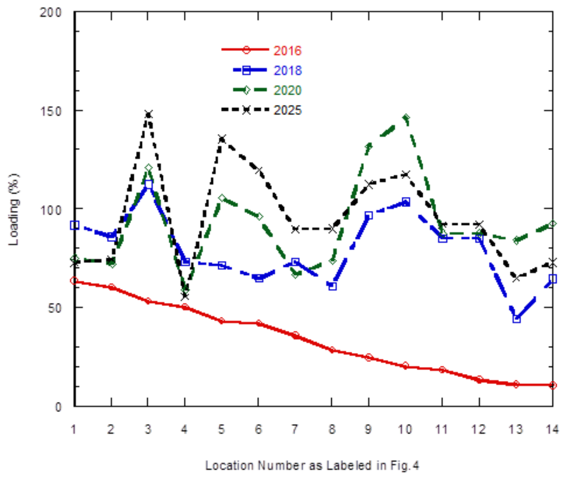
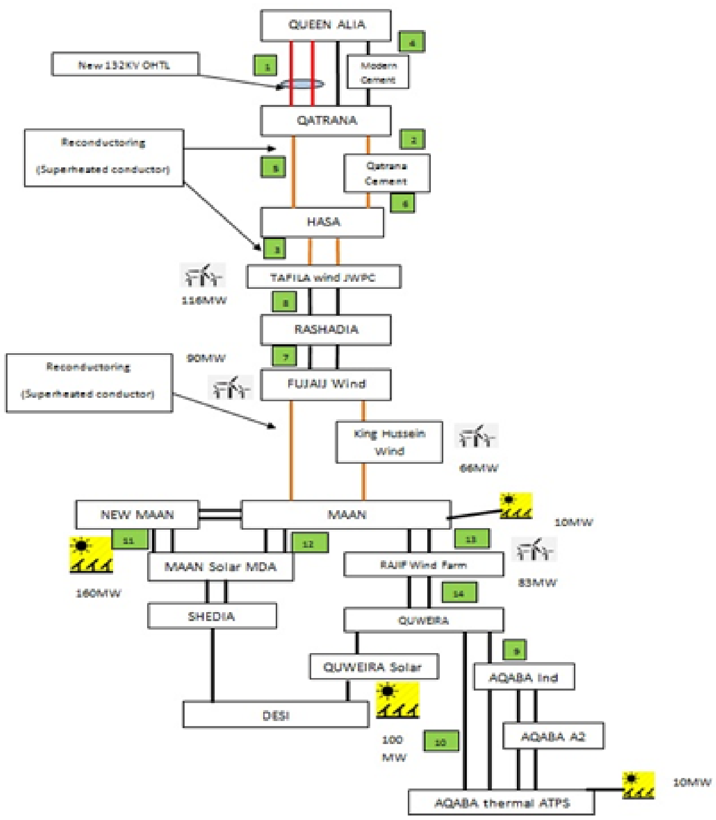


Figure 3. Loading of the 132KV lines in the southern part of Jordan using current grid

To overcome this overloading problems and the presence of bottleneck in the lines from south area to load center, transmission reinforcement is highly needed. It will consist of 400/132/33kV New Ma'an substation with three 400MVA transformers and two circuits 400kV overhead line from New Ma'an to Qatrana with length of 150Km as shown in Fig. 4. The table attached to Fig. 4 shows 14 lines highlighted in that area with names and numbers to be referred to during this work. This reinforcement "Green Corridor" is planned to be constructed starting in 2017. The reinforcements in several 132kV lines will be also considered as part of the green corridor project. It includes replacing the conductors of the lines by superheated conductors which increase the loading limit of the 132 KV Lines to almost double (200%) with current rating of 1500KA compared to the normal existing OHL conductors.

The loading of the 14 selected 132kV lines is studied using DIGSILENT in four target years 2016, 2018, 2020 to 2025, with the presence of the green corridor with year 2016 reflects the current situation. The results shown in Fig. 5 shows the 132 kV grid loading after the constructing the Green Corridor from. The loading results of all 132kV lines in southern area shows that these lines do no experience overloading conditions and, thus, they will be within the thermal rating limits for the next 10 Years.

The reinforcements by Green corridor in the 400kV network are shown in the Fig. 6. The enforcement is needed to accommodate the connection of renewable projects especially in southern area. It includes the New Ma'an 400kV/132Kv substation with three transformers each has capacity of 400MVA and the enforcement in the line (Qatrana- New Ma'an) 400kv with new double circuit also replacing the conductors in 132Kv line.



No	132KV Lines
1	QAIA-QAT X1
2	CMNT-QAT
3	HASA-TAF(1)
4	QAIA-CEMENT
5	QAT-HASA(3)
6	CEMENT -HASA(1)
7	RAS-FUJ
8	RAS-TAF(1)
9	AQI-QUW(1)
10	ATPS-QUW(1)
11	NWMAAN-MDA
12	MDA-MAAN
13	MAAN-RAJIF
14	QWERA-RAJIF

Figure 4. The connection of renewable projects in southern area in 2018 with reinforcement in the 132KV grid

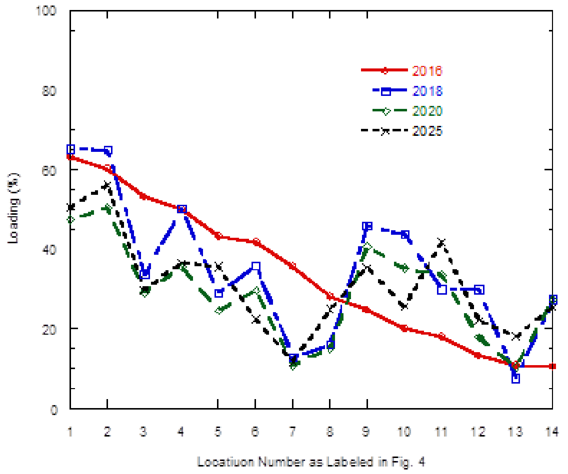


Figure 5. Loading of the 132KV lines in the southern part of Jordan with "Green Corridor"

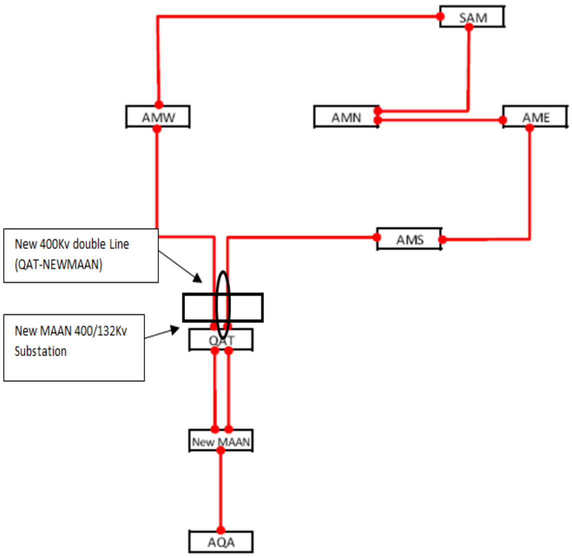


Figure 6. Current Jordanian 400kV grid structure with the reinforcements in the southern part

The lines loading results obtained in DIGSILENT simulation for the 400kV lines with and without the green corridor in the southern part are listed in Table 3. It is clear that this enforcement is needed after 2025.

The sound network condition analysis detected overloading problems in the loading of the following grid components (lines and transformers):

1. 132KV Line ABDOON-AMS.
2. Abdali-HTPS 132KV line
3. Amman South 400/132KV transformers.
4. Amman East 400/132 kV transformer (the third one). These overloading are strictly related to the increase of the demand in the area of Amman.

In addition to that, the presence of overloading in load center substations also should be solved either by expansion, construction of new substation or by transferring load between substations in order to accommodate the huge load growth in that areas, for example, Marqa, Ashrafia, Abdoon, Sahab, etc.

The overloading elements detected after the contingency grid analysis (i.e., N-1 analysis) are highlighted and listed in Table 4. To overcome these overloading problems in the lines and transformers of the grid, recommended transmission network reinforcements and their costs are also given in Table 3. The summation of both transmission reinforcements and generation costs (i.e., total cost) for three scenarios of natural gas prices are calculated and listed in Table 5. For the purpose of better comparison among different technologies of the LCOE is calculated for three scenarios of natural gas prices of 8 $/MMBTU, 10 $/MMBTU and 12 $/MMBTU [13]. It is found that in-spite-of the additional cost of the "Green Corridor" of 145 M$, the LCOE by 2025 will vary only 25 % (between 100 to 125 USD/MWh) when the price of NG increases 50% (from 8 to 12 $/MMBTU). This mainly because of the dependence on RES. It is worth mentioning that the cost of generating electricity in Jordan in 2014 is 223 $/MWh [2]. Thus, with the renewable energy systems and new conventional power plants the LCOE in 2025 will be 43 % less than that in 2014.

Table 3. Comparison of the 400Kv lines loading in the southern part of Jordan with/without green corridor

Year	2016	2018	2020	2025
One line circuit Loading	%	%	%	%
Before Green Corridor				
AQTPS-MAAN X 2	40.80	34.28	28.49	36.20
QAT-MAAN 400 X 2	27.50	35.97	46.78	60.20
After Green corridor	2016	2018	2020	2025
AQTPS-MAAN X 2	40.80	38.00	32.05	57.20
QAT-MAAN(1) 400 X 2	27.50			
QAT-MAAN(1) 400 X4	////	10.98	13.33	21.22

Table 4. Transmission reinforcements needed and their costs until 2025

Network Element	N-1 loading %	Reinforcement Description	Reinforcement cost (k$)
ABDOON-AMS 132KV line	173.8	6.9km/132KVUnderground Cable, double circuit. 2020	1400
Abdali-HTPS 132KV line	115	12.77Km- 132KV overhead, double circuit. 2018	3000
MADABAH-SUWMEH 132KV Line	135.5	20km-132KVoverhead, double circuit.2025	5000
QAIA-MADBA 132KV Line	128.5	19Km- 132KV Reconductering with Superheated conductor.2025	3000
NBAYADER-AMS 132KV Line	126.2	12Km- 132KV overhead, double circuit. 2017	3000
SALT-AMW 132KV Line	122.3	15Km- 132KV Reconductering with Superheated conductor.2017	2200
TAREQ-AMN132(1)	120	5.5Km- 132KV Reconductering with bundle conductor.2020	1000
HASANIND-IRBID 132KV Line	108.3	25Km- 132KV overhead, double circuit.2019	3500
Amman South Transformer	117	Amman South Expansion.2020	7000
Amman East Transformers	110	Amman east Expansion.2018	7000
New Rehab Gen	-	2019	35000
Al Hizam Gen	-	2021	3800
Swaimah Gen	-	2025	2800
HTPS repowering	-	2018	1000
New Aqaba repowering	-	2024	1500
Amman west substation and lines	-	2017	89000
Total Elements cost	-	-	169200
Green corridor cost	-	2017	145000
Total Transmission cost	**-**	**-**	**314200**

Table 5. Overall cost

	Gas Price (8$/MMBTU)		Gas Price (10$/MMBTU)		Gas Price (12$/MMBTU)	
Item	Total discounted cost in M$	Average LCOE (USD/Mwh)	Total discounted cost in M$	Average LCOE (USD/Mwh)	Total discounted cost in M$	Average LCOE (USD/Mwh)
Generation cost	16,669.5	98.59	18,793.7	111.15	20,909.4	123.66
Transmission cost	281.2	1.66	281.2	1.66	281.2	1.66
Total cost	16,950.8	100.25	19,074.9	112.81	21,190.6	125.32

4. Conclusion

In the present work the Jordanian electrical transmission grid modified to reflect the grid situation in each target year up to 2025. Current and proposed generation projects including renewable energy systems are simulated in power system analysis program DIGSILENT. The analysis of the results shows the importance and the need of grid reinforcements in southern area, mainly, the "Green Corridor". The present study showed that such reinforcement is needed to overcome the bottleneck of energy transfer from southern area to load center in north. The analysis is done again but with the green corridor and connection of renewable projects until the target year 2025. As a result more overloaded elements appear in the rest part of Jordanian grid in both normal and contingency cases. These cases are checked and highlighted. Considering the total cost needed for transmission reinforcements and the cost of generation based on three NG prices scenarios, the Levelized cost of energy are calculated, compared and documented. It is found that the LCOE in 2025 will be 43 % less than that in 2014 when the target renewable energy projects and new conventional power plants are delivered.

Remark

It should be noted that part of this paper has been published in GCREEDER 2016 conference**.**

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JJMIE

Volume 11 Number 2, April. 2017
ISSN 1995-6665
Pages 121 -127

Jordan Journal of Mechanical and Industrial Engineering

Evaluation of the Level of Microaccelerations on-Board of a Small Satellite Caused by a Collision of a Space Debris Particle with a Solar Panel

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Received May, 17, 2016 *Accepted April, 5, 2017*

Abstract

The present study aims at studying the effects of possible collision of a space debris particle with a solar panel of a small spacecraft designed to implement gravity-sensitive operating process on-board. We estimated the level of microaccelerations caused by a collision of a space debris particle with a solar panel. The results presented in this article may be useful in the design and operation of modern small spacecrafts and satellites.

Keywords: *Microaccelerations, Collision, Space Debris, Small Spacecraft, Solar Panel.*

1. Introduction

Modern requirements for the design of a new space technology for implementation of gravity-sensitive procedures in space suggest serious limitations of the level of microaccelerations in the area with technological equipment [1]. It is known that the reason for changes of angular velocity of small satellites cause microaccelerations in their internal space can include mechanical moments of various physical nature, effects of various physical fields and executive bodies of control systems, as well as a number of other phenomena [2-4]. Studies show that, depending on the basic parameters of the orbit of the spacecraft, the most significant contribution to the field of microaccelerations of its internal space is provided by the metastable component for low orbits [5-7] or the structural component for high orbits [8-10]. However, modern space projects (such as "OKA-T" [8]) suggest a high level of autonomy of a space lab during orbital flight. This, on the one hand, allows using of high orbits for the spacecraft, reducing the influence of the metastable component [10]. On the other hand, turning off all auxiliary systems on-board the spacecraft, except for the critical ones, for the duration of implementation of operating processes will significantly influence on the structural component. In this case, other disturbing factors may come to prominence in formation of the field of microaccelerations of the internal environment of the spacecraft. One such factor is the collision of a debris particle with the spacecraft.

Improvement of the technologies to control the level of microaccelerations in the technological equipment placement area [11], as well as application of the modern spacecraft control systems [10, 12] reduces the influence of the metastable and structural components on the microaccelerations level. And this, in turn, increases importance of the task of studies of the other disturbing factors influence, in particular, collisions with space debris.

Impact of the space debris particle according to the classification [13] causes, along with the other similar factors, the emergence of a random component of the microaccelerations field. This component is not paid enough attention in the literature. Thus, evaluation of the effect of space debris on microacceleration in the internal environment of large space stations shows that for the "Mir" orbital station the amplitude of such microaccelerations does not exceed 10^{-15} m/s^2 in the frequency range 5-50 kHz [14]. However, the use of small satellites, microsatellites and nanosatellites in the space industry, undoubtedly, will attract the attention of researchers to this problem.

1.1. Simple Evaluation of the Relevance of the Study

Negligible sensitivity of large space stations to impact of the space debris particles differs significantly from the reaction of small satellites caused by similar collisions. In addition, because of their structural complexity, multi-functionality, habitability and permanent need of orbital motion control, large space stations are of little use as prototypes for future space miniplants [8]. Quite the contrary, small spacecraft nowadays are not only capable of fulfilling the role of space minilabs, but also can perform pilot production.

In order to justify the relevance of the problem for small spacecraft, we choose the American spacecraft "Deep Space 1" (Figure 1) launched on 24.10.1998 as a model [15].

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Figure 1. The Deep Space 1 spacecraft and the comet Borelli

The case of a collision of the debris particle with the part of the solar cell mostly remote from the center of mass of the spacecraft area is considered. Spacecraft with solar cell and the space debris particle are considered to be rigid bodies. We estimate the inertial mass parameters of the spacecraft "Deep Space 1" (Table 1), using the data given in [15] and assuming the spacecraft body is a cylinder. As the radius of the cylinder, we take the average of the two characteristic lateral dimensions of the spacecraft. The solar cell is considered as a plate.

Table 1.Estimation of inertial-mass parameters Deep Space 1

Mass of the body, kg	Mass of the panel, kg	Moment of inertia of the body, kg·m^2	Moment of inertia of the panel, kg·m^2
428	58	2264	1099

Parameters of the space debris particles are shown in Table 2.

Table 2. Parameters of space debris particle

Size, mm	Speed, km/s	Impulse, kg·m/s	Impact force, N
0,5	16	0,03	0,15

The reaction time of the collision was estimated as 0,2 s. For example, NASA scientists recorded a meteorite impact on the Moon surface with the duration of about 0,4 seconds, making a 3 m deep crater with a diameter of 14 m [16]. In case of a collision of such a particle with a solar cell (at a distance of 5,9 meters from the center of mass [15]) it causes a moment about 1 N·m. This value is comparable with a moment generated by the orientation engine of «NIKA-T» project (6 N·m [8]) or «SPOT-4» (4 N·m [17]) spacecraft. In this case the resulting tangential microacceleration at the moment of the collision will exceed 100 μm/s^2 at a distance of 0,3 m from the center of mass. This is more than 10 times higher than the permissible microacceleration for "OKA-T" project (10 μm/s^2 [8]). It should be noted that speeds of micrometeoroid particles of natural origin in the vicinity of the Earth's orbit are estimated to be 11-75 km/s [17], so the actual level of microaccelerations caused by the collision may be significantly higher.

For comparison, the same space debris particle with a similar collision with a solar cell of the "Foton-M4" spacecraft will cause tangential microacceleration of two orders of magnitude smaller than the estimate presented above, which corresponds to values close to half of the level of allowable accelerations. Thus, the problem of taking collisions with space debris into account is of practical importance for modern and future small satellites to be used for the purpose of production in space. An example of such a spacecraft is the "Vozvrat-MKA" project [8].

2. Probability of a Collision with a Space Debris Particle

Correct evaluation of the probability of a collision with a space debris particle on the solar cell is a rather difficult task. All natural and man-made particles are divided into observed (with the characteristic size of about 100 mm or more) and unobserved particles. Only a few percent of the total are monitored with optical and radar aids, and the total mass of the man-made objects orbiting the Earth already significantly exceeds 5000 tons [17].

Evaluation of the probability of a collision with a space debris particle with the parameters described in Table II or greater, showing that it will not exceed 10^{-9} per one revolution around the Earth of a spacecraft at a height of the orbit of about 600 km [18]. However, long active lifetime of spacecraft makes this event quiet probable. As evidence, we can point to well-known facts of damage of outer cover (Figure 2) and the solar cell of the International Space Station (Figure 3), and the results of the study of the solar cell dismantled from the Hubble Space Telescope [19], which also has visible micrometeorite craters (Figure 4).

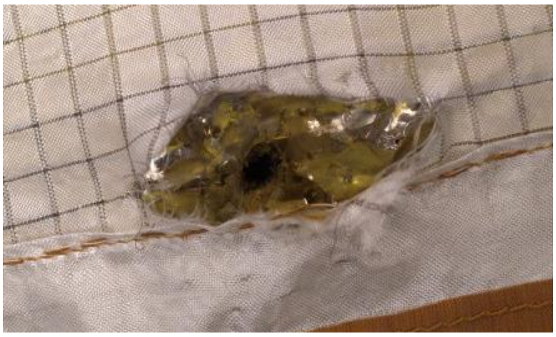

Figure 2. Detail of the damaged outer cover of the International Space Station

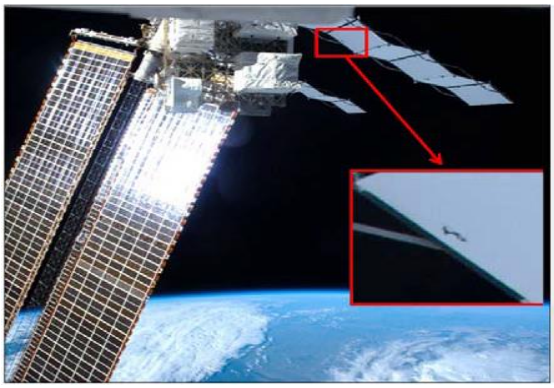

Figure 3. Solar panel of the International Space Station, damaged by a micrometeorite

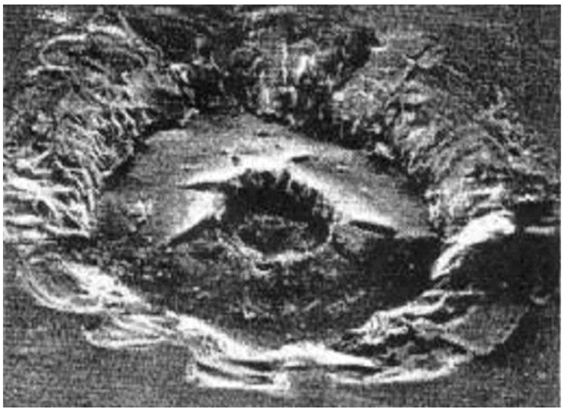

Figure 4. Micrometeorite crater on the surface of the Hubble Space Telescope solar panel

Thus, despite the low probability of a collision with space debris particles in a solar cell of a spacecraft, the considered problem of evaluating accelerations caused by such collisions does not lose its relevance. Firstly, there were actual cases of collisions with such particles in cover of spacecraft, as well as in solar cells. Secondly, the development of the near-Earth space at the present stage leads to the growth of the number of man-made objects, which increases the probability of collisions of spacecraft with space debris particles.

In such a way, this rather weak evaluation of microaccelerations that occur in collisions with space debris particles shows a danger of significant excess of permissible microaccelerations for small spacecraft. On the other hand, during continuous operation of spacecraft in orbit, there is a real possibility of a collision. This justifies the construction of a more complex model of spacecraft for improvement of the earlier evaluation of the resulting microaccelerations.

In addition, at the present time a significant amount of debris particles hinders the effective development of near-Earth space and becomes one of the fundamental problems of the mankind. Space flight experience shows that a high-speed collision of space debris particles with a satellite can lead to the destruction of the individual components of the satellite [20]. Other consequences of a collision may include changes in the angular velocity of the satellite and on-board microaccelerations. For these reasons, the study of the effects of collisions and the development of means of protection of satellites from the space debris is one of the most important international problems [21]. The calculations presented in [22] show that for a collision of a nanosatellite with high-speed particles less than one millimeter in diameter, there is a significant change in the magnitude and direction of rotation of the nanosatellite.

3. Simulation of a Collision of a Particle and a Satellite in the Form of a Rigid Body

There is viewed motion of the satellite about its center of mass on the example of a small "Deep Space 1" spacecraft with mass of 486 kg and dimensions 2.1x1.7x1.5 m (Table 1). Small interplanetary station "Deep Space 1" was intended for a long flight through the solar system, and could be open to collision with micrometeorite or space debris. Assume that a collision of "Deep Space 1" with a space debris particle takes place in a circular near-Earth orbit at the altitude of 600 km. This formulation is relevant for development of space miniplants that are expected to operate in the near-Earth space. The simulation takes into account a number of different positions of the point of collision in different directions of the vector of the relative collision velocity [23]. It is assumed that the debris particle is a ball of 0.5 mm in diameter. Before the collision with the satellite, the particle moves with a relative speed of 16 km/s.

A mathematical model describing the rotational motion of the satellite as a rigid body after the collision with the high-speed particle includes a system of three dynamic Euler equations and a system of four equations for determining the Rodrigues-Hamilton parameters [24].

Dynamic Euler equations describing the change in the angular velocity of the satellite, written in a vector form, are as follows:

$$I\frac{d\vec{\omega}}{dt} + \vec{\omega} \times I\vec{\omega} = \vec{M}, \tag{1}$$

Here I is the tensor of inertia of the satellite; $\vec{\omega} = (\omega_x,\ \omega_y,\ \omega_z)$ is the vector of the angular velocity of the satellite including projections on the axes of the associated XYZ coordinate system; $\vec{M} = (M_x,\ M_y,\ M_z)$ is the vector of external mechanical moments acting on the small satellite. With a disabled control, the vector of the mechanical moment includes perturbing gravitational and aerodynamic moments recorded in known forms.

Differential equations for Rodrigues-Hamilton parameters $\lambda_1,\ \lambda_2,\ \lambda_3, \lambda_4$ are as follows [25]:

$$\begin{aligned}
2\frac{d\lambda_0}{dt} &= -\omega_x\lambda_1 - \omega_y\lambda_2 - \omega_z\lambda_3,\\
2\frac{d\lambda_1}{dt} &= \omega_x\lambda_0 - \omega_y\lambda_3 + \omega_z\lambda_2,\\
2\frac{d\lambda_2}{dt} &= \omega_x\lambda_3 + \omega_y\lambda_0 - \omega_z\lambda_1,\\
2\frac{d\lambda_3}{dt} &= -\omega_x\lambda_2 + \omega_y\lambda_1 + \omega_z\lambda_0.
\end{aligned} \tag{2}$$

The numerical integration of the dynamic Euler equations (1) and the kinematic equations (2) allows us to find the components of the angular velocity of the satellite and the values of the Rodrigues-Hamilton parameters, respectively. To calculate the quasi-static component of the microaccelerations on-board of a small satellite considered as a rigid body in a fixed point relative to the satellite, we apply a well-known expression [5, 14, 26]:

$$\vec{w} = \vec{r}\times\frac{d\vec{\omega}}{dt} + (\vec{\omega}\times\vec{r})\times\vec{\omega} + \frac{\mu_e}{|\vec{R}|^3}\left(\frac{3(\vec{R}\cdot\vec{r})\vec{R}}{|\vec{R}|^2} - \vec{r}\right) + \vec{w}_a, \quad (3)$$

where $\vec{w}$ is the microacceleration vector including the effect of inertia (first two terms), gravity (the third term) and air resistance force (the fourth term); $\vec{r}$ – radius vector defining the position of the point with respect to the center of mass of the satellite; $\vec{R}$ – radius vector of the center of gravity position in the geocentric coordinate system; μ_e – Earth's gravitational parameter. During disabled active control of the satellite orientation it is assumed that the value $\vec{w}_a$ is determined, taking into account the disturbing action of air resistance force.

It is known [27] that in the process of collision of a particle and a rigid body, penetration of the former into the body material is observed, accompanied by release of crushed material from the body structure. In this case, the ratio of jet impulse at ejection to the particle impulse can be calculated, for example, as follows [27]:

$$\frac{J_0}{J_p} = \frac{3u_0}{5u_k}, \quad (4)$$

Here u_0 is the relative velocity of collision of the particle and the body, u_k is the minimum value of the collision speed causing fine crushing of the body material. According to our supposition, u_0 = 16 km/s, and u_k = 1 km/s. In this case, we obtain from the expression (4) that the jet impulse at ejection of material J_0 exceeds the impulse of the space debris particle J_p by about 10 times.

4. Numerical Simulation

Figures 5-6 show the results of the numerical simulation of the process of changes in the components of the angular velocity and microaccelerations on-board the "Deep Space 1" satellite. The horizontal axis shows the time of orbital flight of the "Deep Space 1" satellite, measured in hours.

In the process of numerical simulation it was assumed that the initial angular velocities are due solely to the impact of high-speed particles. In drawing of Figures 5-6 it was taken into account that the collision takes place in the most remote from the center of mass point of the deployed solar cells. In this case, the angular moment of the space debris particle becomes completely transformed into kinetic moment of the "Deep Space 1" satellite.

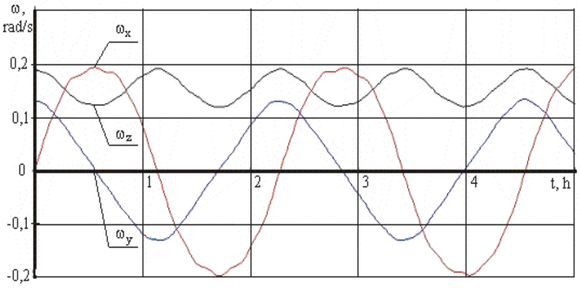

Figure 5. Change in components of the angular velocity of the satellite Deep

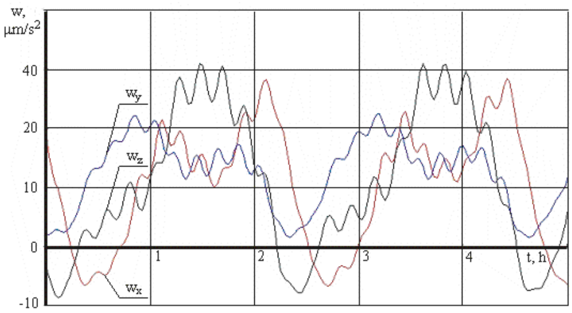

Figure 6. Change in components of the vector of the on-board quasi-static microaccelerations of the satellite Deep Space 1 as a rigid body

The simulation results show that for an aluminum particle with a diameter of half a millimeter, having a relative velocity before the collision of 16 km/s, the components of angular velocity of the satellite after the collision do not exceed 0,2 radians per second. In this case, the microacceleration in most remote point from the center of mass does not exceed 35 μm/s^2.

In the numerical simulation of the rotational motion of the satellite we take into account the effect of the jet moment on the satellite design. Furthermore, it is assumed that the collision does not occur through failure of the satellite structure, and the action of the jet impulse only results in the rotation of the satellite.

It should be noted that these assumptions lead to an overestimation of the results of estimates of magnitudes of angular velocities and microaccelerations. Indeed, in general case the process of high-speed collision in vacuum is a complicated multiphysical phenomenon [28].

In this formulation of the problem of a collision with a space debris particle the small satellite was supposed to be a rigid body. Assessment of the accelerations values that occur in collision of a high-speed space debris particle with an elastic deformable solar panel is also of practical concern.

5. Simulation of Oscillations of a Solar Cell Caused by a Collision with a Space Debris Particle

For evaluative calculations we use the following assumptions:

1. **Model of a Solar Panel as an Euler-Bernoulli Beam**

This model suggests an overestimation of microaccelerations [8], because the oscillations of the beam are only possible in the longitudinal direction. At the equal value of the potential energy of deformation the amplitudes of the oscillations are higher than the amplitudes of the oscillations of a plate where both longitudinal and transverse oscillations are possible.

2. **Model of a Solar Panel Mounted to the Spacecraft Body-Rigid Mounting**

This model also overestimates the microaccelerations, as part of the oscillation energy dissipates in the elastic attaching fitting. However, the requirements of the effective use of solar panels necessitate a quite rigid mounting to the body. Otherwise, it would be impossible to ensure the right orientation of the solar panel to the Sun. If we exclude energy-intensive processes, e.g. high resolution imaging of the Earth's surface, panel's resilient mounting to the body becomes possible. A striking example of such design can be «SPOT 4/5», a series of French spacecraft [1]. However, for space labs (for example, «NIKA-T») the cosine of the angle between the normal line to the surface of the solar panel and the direction towards the Sun must be greater than 0.9 [8].

On the other hand, some spacecraft use active dampers of natural oscillations of solar cells, reducing the oscillation damping duration from 90 s to 18 s [29]. However, in this case, this means not only an overestimation of the amplitudes of the microaccelerations, but also the period during which the favorable conditions for gravity-sensitive experiments will be disrupted.

3. Movements of the Center of Mass of a Spacecraft Body are Negligible Compared with the Movements of the Center of Mass of the Solar Panel

This simplification allows us to consider oscillations of a solar panel, the fastening point (fitting) of which is rigid. Accuracy of this simplification can be easily estimated. For the considered "Deep Space 1" spacecraft the ratio between the displacements of the centers of mass of the solar panel and the spacecraft body will correspond to the ratio of the mass of the cell to the whole mass of the spacecraft, i.e., $29/486 \approx 0{,}0597$. At that, the evaluation is greatly simplified.

It is known [30] that oscillations of rigidly attached beams are determined with accuracy up to an arbitrary constant C with by the following equation:

$$y(x;t)=\sum_{i=1}^{N} C_i\left[U(k_i x)-\frac{V(k_i l)}{S(k_i l)}V(k_i x)\right] \quad (5)$$
$$Cos(\omega_i t)$$

where $y(x;t)$ is the deviation of points of the solar cell from the non-deformed position; N is the number of accounted natural modes; ω_i are natural frequencies; C_i is a part of the constant C attributable to the i-waveform; Krylov functions: $U(k_i x)=0{,}5(chk_i x-\cos k_i x)$; $V(k_i x)=0{,}5(shk_i x-\sin k_i x)$; $S(k_i x)=0{,}5(chk_i x+\cos k_i x)$; $k_i=\frac{\mu\omega_i^2}{EI}$; μ and EI are accordingly mass per unit length and rigidity of the solar panel.

To determine the constant C it is necessary to calculate the dynamic deflection of the end point of the beam [31]. We shall consider the most dangerous case, when the particle collides with the extreme end point of the panel. This situation is similar to the formulation of the problem of evaluation of accelerations in the previous sections of the present study. According to a study [32], in the case of high velocity impact the dynamic deflection is about 1,57 of the static deflection.

Mass and velocity parameters of the particles used in the previous section determine the force at the moment of impact interaction that is equal to 0,2 N [33]. After that, we can determine the static bending, using this value and the universal equation of the elastic axis of the beam [31], which for this case will be:

$$y_{st}=\frac{Ml^2}{2EI}+\frac{Fl^3}{6EI},$$

here M and F are static reactions of the fitting at loading beam strength of 0,2 N on its free end. Substituting the value: $y(x;t)=1{,}57y_{st}$ for $t_0=0$ in (5), we can obtain a constant value C.

After that, we performed further numerical simulation taking into account the different number of natural modes. Figure 7 shows the dependence of the change of microaccelerations caused by fluctuations in the solar panel at collision with a space debris particle, taking into account the first five forms of natural oscillations.

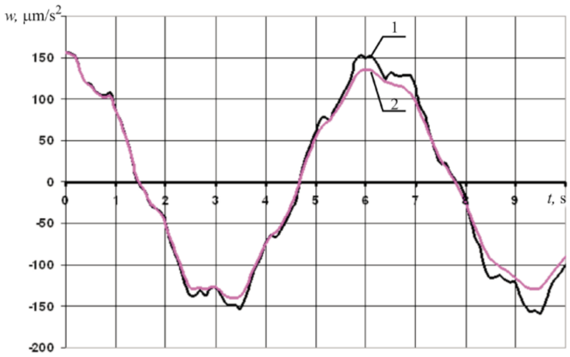

Figure 7. Change in the accelerations caused by oscillations in the solar cell:

1 - without taking into account the damping; 2 - taking into account the damping when the cell frame is made of MA-2 material

As seen in Figure 7, the caused microacceleration substantially disrupts favorable conditions for the successful implementation of gravity-sensitive processes. Taking into account the damping, the period of unacceptably high microaccelerations in respect of "OKA-T", a perspective Russian space laboratory project (the maximum value of the magnitude of microaccelerations is 10 μm/s^2 [8]) is about 200 s.

6. Conclusion

Thus, the conducted researches show that collision of a small high-speed particle with a solar panel may disrupt favorable conditions for gravity-sensitive processes in a small spacecraft. The estimates of on-board quasi-static microaccelerations caused by the collision with a space debris particle for the parameters of "Deep Space 1" spacecraft demonstrate the possibility of quasi-static microaccelerations up to 35 μm/s^2. This exceeds the permissible level of microaccelerations for "OKA-T" project in 3,5 times [8]. Given the fact that the quasi-static microaccelerations are hardly damped over time, it can become a serious problem for the implementation of gravity-sensitive processes.

On the other hand, recently developed processes require for their successful implementation accelerations is no greater than 1 μm/s^2 [34]. Of course, in the future these requirements will only increase.

Simulation of the solar panel oscillations shows a possibility of microaccelerations with amplitude close to 150 μm/s^2. Their frequency depends on the parameters of the solar cell (in this example, "Deep Space 1" spacecraft dominant frequency is about 0,2 Hz). In this case the permissible values for "OKA-T" project will be exceeded in about 200 seconds. This will cause failure of all the gravity-sensitive processes taking place in this period. As collisions with a space debris particle are random phenomena, there is a doubt that no production processes or orientation maneuvers of the satellite would be taking place at the moment of the collision.

Thus, the problem of disruption of favorable conditions for gravity-sensitive processes in a small spacecraft due to collision of a solar cell with high-speed space debris particles or other particles is of high importance and requires close attention.

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JJMIE

Volume 11 Number 2, April. 2017
ISSN 1995-6665
Pages 129 -140

Jordan Journal of Mechanical and Industrial Engineering

Critical Success Factors for Soft TQM and Lean Manufacturing Linkage

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Received Aug., 4, 2016 *Accepted March, 2, 2017*

Abstract

Implementation of Total Quality Management (TQM) and Lean Manufacturing (LM) is a common goal for manufacturers to be leaner. While many studies have investigated TQM and LM separately, the present paper explores the Critical Success Factors (CSF) for these practices together in one model focusing on the soft dimension of TQM. A structured closed questionnaire was distributed to operations managers in Malaysian industries. A 5-point Likert scale was used in designing the survey questionnaire. One hundred and two responses were collected in this preliminary study. Results obtained through Principal Component Analysis (PCA) showed that both latent contracts are reliable. Both KMO and Bartlett's test were measured to ensure the adequacy of the practices. Three CSF (3) were extracted for Soft TQM aspects while Seven (7) factors were extracted for LM practices. Results obtained from PCA indicated that Malaysian managers are involved with LM wastes, Kaizen, Just in Time, continuous flow, TPM, Workforce Management, standardized work practices, strategic planning and human aspects. The novelty of the present study stems from the realization of TQM and LM aspects that determine the priorities of Malaysian managers in manufacturing environment by providing guidelines about the most important factors to adopt.

Keywords: *Soft TQM, Lean, Success, Factor, Questionnaire.*

1. Introduction

Both LM and TQM have received much attention from practitioners and researchers in developing and developed countries. Researchers [16] argued that Operations Management (OM) practices such as supply chain, TQM, and LM are applied separately inside enterprises and there is possibility for the integration among these practices that can optimize processes. Although there are many studies conducted on these practices, still, there is a number of questions that remain unclear regarding the applicability of these initiatives [8].

TQM is a vital management tool in ensuring companies can be successful in the continuously growing competition in the global market [9]. Scholars [67] have integrated the Leadership practices in terms of TQM and LM based on the adaptation from several world class awards companies, models and system. Nowadays, Muda (waste) become an important concept for Toyota Production System (TPS). Thus, LM wastes are considered as the DNA for TPS. However, LM is aligned with TQM environment for continuous improvement. Furthermore, more scholars suggested TQM could be categorized into two distinct groups, namely soft TQM and hard TQM ([60]; [33]). Hard TQM tends to use more practical, numeric, and systematic quality-control tools; soft TQM focuses on long-term natures and is more humanistic, it is the human side and people-related TQM [76].

Researchers [6], in their study, argued that there is too much Muda in USA manufacturing system which can be classified as: Muda of workers, Muda of over production, Muda of inventories and excess processing, Muda of defects, Muda of waiting, Muda of movements of materials around factory and Muda of facility. There is paucity in studies that address the impact of LM on the sustainable performance [74]. Both TQM and LM have various ideas and views, and scholars are questioning if they are the same or not? [7]. Different papers reported that TQM and LM can bring more benefits to a company but there is still a lack in case studies on companies that have implemented both initiatives [61].

Limited research has been conducted in the critical elements of LM. According to [56], TQM has been practiced in diverse industries from manufacturing to services. In addition, [10] concluded that issues and common points regarding TQM and LM are not clear. Others argued that TQM considered as tools and techniques of LM [39]. Both are covered in different divisions. For instance, the effect of TQM on employee

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satisfaction and loyalty in government [17], LM tools effectiveness in government [57], change management for adoption of lean principles in distribution centers [41], Integrate Lean, Six Sigma and Logistics into a consistent process [35], Effect of Lean Thinking on functioning of Emergency Departments [38], Development of a lean system for improvement in the healthcare organizations [21]. Authors in the present paper investigate the linkages among these two philosophies to understand in depth the most relevant Critical Success Factors (CSF) for both TQM and LM. Thus, the objective of the present paper is to propose a model to show the linkages between Soft TQM and LM practices and conducting an empirical investigation through the preliminary study in Malaysian industries.

1.1. Objectives of the Study

The present paper aims to explore and identify the success factors for both LM and Soft TQM practices. Further it aims to identify these practices as it depicted from numerous industrial sectors in Malaysian environment. Besides, using modern techniques form statistical package using different practices refer to data reduction through principal component analysis is another aim in the present paper.

The remainder of the present paper is structured as follows: the next section is for reviewing the literature of TQM and LM. This is followed by proposing the model and depicting the methodology and designing the structured questionnaire. Finally, the paper introduces the techniques employed from SPSS to estimate the reliability and extract the necessary factors. Conclusions, limitation and future directions end the work in the present study.

2. Literature Review

In the present paper, literature review comprises different sections in order to understand the linkages among soft TQM and LM practices.

2.1. Total Quality Management (TQM)

TQM is an extended version of the classical production process involving the entire organization and all its functional areas [4]. Researchers [24] define TQM as a management philosophy which aims to contribute continuous improvement in the organization with the participation of all employees to achieve customer satisfaction by producing better, cheaper, faster and safer than competitors. Generally, TQM is classified into soft and hard TQM. Different researchers utilized different factors for each aspect. Thus, plenty of definitions for TQM appeared in the literature. TQM means that quality involves everyone and all activities in the company. Quality means conformance to specifications (meeting customer requirements). Management means that quality can and must be managed [48]. TQM is most commonly seen as a set of dimensions, e.g., leadership, people management, customer focus, supplier management, planning, process management and continuous improvement [1]. According to [48], TQM comprises some primary activities: Business System Planning (BSP), Quality Function Deployment (QFD), Critical Success Factors (CSF) and Balanced Scorecard (BSC).In addition to manufacturing sector, [5] studied the impact of TQM and operational flexibility on hospitals performance.

In the present study the soft dimensions of TQM is taken into consideration upon proposing the conceptual model for several reasons; (1) to be consistent with the conclusions of [51] that the majority of studies agree that soft TQM elements have a crucial role in TQM implementation, (2) ISO 9000 which is a driver to TQM implementation, comprised some elements related to soft TQM, such as management responsibility, customer focus, and (3) Soft TQM aspects have a leading role in TQM implementation and deriving benefits [55], (4) the human factor is a fundamentally important aspect of the implementation of TQM in organizations, (5) quality improvement is influenced mainly by soft TQM elements (however, there is no uniform definition for soft TQM today), and (6) because some scholars suggest that TQM failure is due to deficiencies in soft TQM elements [76]. This justifies why the prsent paper focuses on the soft aspects of TQM.

2.1.1. Soft TQM (STQM)

Although some scholars have begun to discuss the significance of soft TQM, there is little agreement as to its primary construct and statement [76]. According to [76], the constructs of soft TQM are variable by different scholars' practices. Several researchers have suggested different soft and hard factors for TQM. Hard factors are related to the techniques and tools, such as statistical process control and problem solving methods while the soft TQM refer to the "management" part of the TQM which involves people, culture and improvement [25]. They proposed a framework which is comprised of ten different factors for soft TQM. In their study, [3] investigated the linkages among the two dimensions of TQM, namely soft and hard. Researchers [76] consolidated the elements of soft TQM into the following: management leadership, employee fulfillment, employee involvement, training and education, strategic quality policy, and customer focus. Researchers [71] classified the management tools and techniques as hard aspects of TQM and management concepts and principles as the soft side of TQM.

2.2. Lean Manufacturing (LM)

Shah *et al*. [62] argued that LM is clustered into three categories, namely (1) philosophy, (2) practices, and (3) principles. On the other hand, [22] argued that these practices and principles must be designated in an order, such as moving from TQM towards LM. Moreover, [2] argues that the use of the tool and technique for LM is not enough, and has found that companies faced difficulties in implementing LM and could not receive the full benefits because they focus in the lean tools and techniques only (hard lean and do not focus on the human side (people) which is a soft lean. According to Shah and Ward [63], the definition of LM highlights mechanisms needed to achieve the central objective of waste elimination. In other words, LM is production of goods using less of everything. LM can be defined as "an integrated socio-technical system whose main objective is to eliminate waste by concurrently reducing or minimizing supplier, customer, and internal variability". Its focus on the reduction of waste improves the customer value.

The goals of using LM in companies are to generate less waste, less human effort, less manufacturing space, less investment in tools and less engineering to develop a new product [7]. Lean thinking or lean production is the same as TPS [18]. Since 1996, the term lean thinking has become as famous as lean production especially in Western industry. Lean has many tools and principles. Previous studies considered LM in different perspectives. For instance, [34] measured LM using one (1) dimension, [66] used six (6) dimensions for LM, [63] adopted ten (10) dimensions, [52] utilized five (5) dimensions, and [43] utilized eleven (11) different LM tools.

2.3. Total Quality Management and Lean Manufacturing Linkage

The present paper is vital because it discusses and assesses the effects of Soft TQM and LM critical success factors (tools and techniques) together in the Malaysian industries'. Researchers discussed that TQM, which comprises hard aspects including the different tools and techniques, is designed to implement LM principles [72]. In general, both TQM and LM have similar goals which are waste reduction, improving performance and the continuous improvement [70]. Moreover, researchers [10] concluded that LM journey is deeper and more widespread as compared to TQM Journey. Wilson [73] argued that if TQM is carefully implemented alongside a kaizen event, it leads to customer satisfaction and that it is considered among the key tools that are often used to facilitate the implementation of the kaizen process which is an important factor for LM. These practices are considered as the most popular initiatives adopted by manufacturers [42]. Researchers [46] concluded that there is a lack of literature studying the simultaneous impact of lean production and TQM on operational performance. [59] explained the fundamental concept of TQM and LM as "if waste can be eliminated, then the profit will go up by the same quantum for an organization". The study conducted by [7] revealed that TQM and LM have much in common. An Integrated TQM with LM is a system which comprises their principles. This system focuses in achieving total customer satisfaction by removing eight wastes available in any process in an organization [66]. According to [32], both tools on lean thinking and TQM have one thing in common, which is the continuous improvement to deliver superior value to the customers. [59] stated that there is no doubt that Kaizen (which is an LM tool) is part of TQM. Furthermore, he concluded that LM comprises many good concepts; all of them are principles/ strategies of TQM. However, TQM is the superset encompassing LM. According to [54], LM philosophy advocates TQM as an approach aimed at reducing manufacturing process variance. They found that JIT and TQM have a direct and positive effect on operational performance. These bundles confirm their roles as the pillars and cornerstones of LM.

3. A Proposed Conceptual Model

To understand the relationships among the practices, the conceptual model is developed. The present paper is based on the proposed model which comprises two multidimensional latent constructs. Figure 1 depicts a path diagram and illustrates cause- effect relationships for the study model. Its causal structure comes from the extensive literature review of the published material. It considers the impact of different factors for TQM on LM dimensions as postulated from the literature review. It is understood that an integrated TQM with LM is a system which comprises TQM and LM principles. Figure 1 shows the schematic presentation of the proposed model. Structural equation modeling techniques are necessary to understand the linkage among soft TQM and LM tools and techniques which is among the future agenda of the present paper. According to [15], TQM implementation is an initial step before implementation of LM. [53] argued that if enterprises have to build a good quality management system, it is necessary to integrate TQM with other similar concepts such as LM.

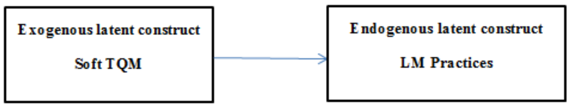

Figure1. Proposed model. Adapted from [15]

4. Methodology

4.1. Design Approach

The design of the present paper is based on a quantitative approach. A structured questionnaire is designed in order to empirically validate the proposed model. The questionnaire consists of two sections related to TQM and LM aspects. All items used are based on 5 points Likert scale. A closed structured questionnaire, as a tool for data collection, was utilized by different researchers including [14], [12], [52], and [76]. It was sent through email to different scholars and academics to modify and revise the items. As a result, the items of the questionnaire were modified. It focused on the measured manufacturing sectors in Malaysia since the manufacturing sector is considered as the backbone of the developing industry [26]. Two directories were followed in order to cluster the certificated industries, namely Federation of Malaysian Manufacturers [30] and through SIRIM website http://www.malaysiancertified.com.my/. Authors critically reviewed these directories until a final list of the certified industries was obtained. The classification of the certified companies in this sector was grouped into twenty four categories which consist of the different manufacturing sectors, indicated in Table 1. A stratified random sample was selected from this list. One hundred and two responses were finally obtained from the respondents' managers and considered an acceptable to run EFA for data reduction.

Table1. Measured manufacturing sectors. Based on [30]

Sector	**Total companies**
manufacture of plastic products	208
manufacture of rubber products	105
manufacture of other nonmetallic mineral products	196
manufacture of chemicals and chemical products	272
manufacture of basic metals and fabricated metal products	384
manufacture of food products and beverages	157
manufacture of electrical machinery and apparatus	147
manufacture of machinery –automotive	9
manufacture of machinery and equipment	117
manufacture of wood and wood products	36
manufacture of furniture	31
manufacture of paper and paper products	85
manufacture of printing, publishing, and reproduction of recorded media	29
manufacture of motor vehicles, trailers and semi- trailers	29
manufacture of other transport equipment	12
manufacture of coke, refined petroleum products and nuclear fuel	19
manufacture of medical, precision and optical instruments, watches and clocks	23
manufacture of wearing apparel, tanning and leather	19
manufacture of textiles	23
manufacture of radio, television and communication equipment and apparatus	52
manufacture of Tobacco products	3
manufacture of office, accounting and computer machinery	10
Recycling	3
other manufacturing activities not elsewhere classified	22
Total	**1991**

4.1.1. Sample Size Justification

With reference to SIRIM web site and FMM 2015 directory, 1991 certified industries in the different measured manufacturing sector are determined as industries certified to ISO 9001 QMS. As per the recommendations of Zainudin [78] exploratory factor analysis can be done on a sample of 100 basically for the pilot study gathered data. The study conducted by Habidin and Yusof [40] to determine Lean Six Sigma(LSS) construct, in the automotive industry in Malaysia, used a pilot study as 100 questionnaires sent to respondents, 57 were completed and gave response rate of 57 percent. *Authors of the present study sent 240 questionnaires to respondents in the pilot study, which is consistent with the guidelines assigned by Habidin and Yusof [40]*

4.2. Operationalization of the Constructs

In the present paper, both exogenous (TQM) and endogenous constructs (LM) are hypothesized as multidimensional constructs. Soft TQM is characterized and proposed by 20 indicators adapted from related literature whereas LM is characterized and proposed by 64 different indicators. These indicators are adapted from the literature review and both content and face validity were conducted in order to examine the validity and confirm the adequacy of the instruments used. The designed questionnaire was refined by academics from Malaysia, India, Palestine, Australia, USA and others. Upon receiving feedback from experts consulted in the field, questionnaire items were revised again. The following sections introduce the main hypothesized dimensions for both soft TQM and LM.

4.2.1. Soft TQM Dimensions

The items for Soft TQM are illustrated in Table 2. After considering the comments from the experts in the field, it is proposed that there are three main dimensions that can define the aspects of the soft dimension of TQM. These are: (i) strategic planning, (ii) human resource focus, and (iii) strategic quality policy. These are customized from the main concept of TQM philosophy or termed as people and human resources aspects. Strategic planning consists of seven items; human resource focus consists of six items and, finally, strategic quality policy consists of seven items. It is notable that these items are derived from valid and reliable instruments investigated by other scholars in different environments and the present study investigates these in the developing economy of Malaysia.

Table 2 . Soft TQM dimensions

#	Items	Study	Dimension
STQM1	Our company has clear, strategic objectives.	[66]	Strategic planning In general, there is not a commonly accepted definition for strategic planning. Coşkun [20] considers it as a component of strategic management. [13] defines strategic planning as "a deliberative, disciplined approach to producing fundamental decisions and actions that shape and guide what an organization (or other entity) is, what it does, and why". [20] argued that Strategic Planning is the initial stage and foundation of strategic management. Likewise, strategic quality management is among the major components of TQM.
STQM2	In our company, strategic objectives and plans are effectively communicated to all staff.		
STQM3	In our company, every staff member is aware of our strategic objectives and the action plans to be accomplished.		
STQM4	In our company, staff members are committed toward our strategic objectives and action plans.		
STQM5	We integrate public responsibility into performance improvement efforts.		
STQM6	Our staff adheres to a formal code of ethics.		
STQM7	We lead the efforts to improve the community services, such as education.		
STQM8	In our company TQM is successfully implemented, because Jobs and work for quality management are carefully designed.	[27]	Human resource focus (HR) is giving importance to employee in terms of providing opportunity to excel. Employees must be recognized for their achievements and equally rewarded to motivate them to perform better. Creating an environment where only merit gets berth. Training & development is an important activity which prepares the employee to respond effectively and efficiently towards changing business environment. Empowering employees is one of the most important aspects for building superior culture [27]. According to [20] Human Resources Management is the soft dimension of TQM. In TQM, providing employees with necessary training and ensuring the involvement of employees are necessities. Scholars [11] found that HR and strategic planning are among the key aspects that lead to strength of organizations.
STQM9	In our company TQM is successfully implemented because flexible work system exists.		
STQM10	In our company TQM is successfully implemented because effective communication takes place		
STQM11	In our company TQM is successfully implemented because employees are recognized for accomplishing their work related to quality programs.		
STQM12	In our company TQM is successfully implemented because employees are given adequate compensation (salaries and benefits) related to quality programs.		
STQM13	In our company TQM is successfully implemented because education and training are provided related to quality programs.		
STQM14	Our company has a clear long- term vision statement.	[76]	Strategic quality policy According to [76], Strategic quality management is the process of establishing long range quality goals and defining continuous improvements to meet organizational goals, such as improving processes, products, and service.
STQM15	Our company has an effective quality improvement plan.		
STQM16	Quality goals and policies are well communicated to the employees within the company.		
STQM17	The processes for designing new products and services in our company ensure quality.		
STQM18	In our company, employees involved in different processes know how to use statistical controlling methods to evaluate their processes.		
STQM19	Our company has a career road map for employees.		
STQM20	Our company encourages continual study and improvement of all of its products, services, and processes.		

4.2.2. LM Dimensions

On the other hand, the dimensions of LM include both soft and hard LM practices consisting of the different tools and techniques. It is proposed that these aspects together can minimize the wastes and the production costs. These dimensions are depicted in the following Table 3. The present paper produced a comprehensive LM model which proposed to consist of eleven different dimensions. These dimensions were adapted from previous valid and reliable instruments and refined by the experts and academics from different countries including Malaysia, India, Australia, Palestine, and others. In addition, the dimensions included in this section are adapted from Toyota Production System (TPS) model and revised to be consistent with the Malaysian environment. According to [50], LM is an integrative concept which can be adopted by selective set of keys or factors which are considered critical for successful implementation.

Table 3. LM proposed dimensions

Dimension	Definition	# Items	Reference
JIT delivery by suppliers	Just- in- time by using the quantity needed, the time frame required and assuring the best quality of product for the customer and this to operate in a faster way [45]	5	[14], [53], [12]
Setup time reduction	Setup reduction is a very useful lean tool for enterprises to eliminate wastes and improve production efficiency. It is an important tool in LM to realize quick setup change and meet the demands of individualized customers [19]. Setup time is total elapsed time from completion of the last good part from the previous setup to the first good part from the new setup.	6	[14], [58]
Continuous flow	Manufacturing where work-in-process smoothly flows through production with minimal (or no) buffers between steps of the manufacturing process. It eliminates many forms of waste (e.g., inventory, waiting time, and transport) [47]	6	[12], [58]
Total productive maintenance	Total productive maintenance ensures a better performance of the equipment by maintaining them in a good condition thus reducing the risk of troubleshoot and failure [45]	6	[12], [58]
Workforce Management	Workforce management affects flexibility because LM practices promote multi-skilled workers who can easily be assigned from one work center to another as dictated by production volume([75]; [44])	6	[44]
Kaizen	aims to involve all employees in the operation process and this training them and coaching them on their tasks([45]	6	[49], [58]
Waste Elimination	LM seven wastes, namely Over –production, Waiting, Transportation, Inventory, Over-processing, Motion, Defects [23].	7	[28]
5S Practice principles	The 5S is meant to be self-sustaining and the benefits are the results of a disciplined workforce [79], 5S steps are sorting (to eliminate useless items), shining (to keep workplace clean), setting in order (to keep everything in place), standardizing and sustaining (to assure continuity).	7	[31]
Kanban	It is a subsystem of the LM system which was created to control inventory levels, the production and supply of components [65]	5	[14], [36]
Standardized Work	To eliminate unnecessary inventory by the first line supervisors [45]	5	[69], [58]
Hejunika	A form of production scheduling that purposely manufactures in much smaller batches by sequencing (mixing) product variants within the same process. It Reduces lead times (since each product or variant is manufactured more frequently) and inventory (since batches are smaller).	5	[69], [58]

5. Results

Results of the present paper are summarized in three sub-sections; reliability analysis of the constructs is presented first while the remaining sub-sections are concerned with the exploratory factor analysis results. SPSS 22 was used to analyze the data gathered during the period September 2015 and January 2016 in this preliminary study.

5.1. Reliability Analysis

Shah *et al*. [64] considered that reliability of the instrument is most important during data collection phase. To calculate the reliability of the model, cronbach alpha was calculated for both STQM and LM dimensions and items, respectively. This was done through the statistical package for social science (SPSS 22). In the present paper, the reliability of the model will be estimated twice, before doing the EFA and after extraction the factors. Results showed that the latent construct is reliable as it is greater than the threshold (0.7) as recommended by [37]. This is depicted in Table 4.

Table 4. Reliability analysis for latent constructs

Construct	No. items	Cronbach Alpha	Result
Soft TQM	20	0.890	Acceptable
LM	64	0.920	Acceptable

From the results shown above, authors conclude that the proposed model in the present paper is reliable since cronbach alpha for all constructs and items are greater than the threshold value which is 0.7. This encourages authors to proceed with the next phase for data reduction.

5.2. Exploratory Factor Analysis (EFA)

Factor analysis is used for data reduction. In the present paper, it is applied for both Soft TQM as the exogenous and LM latent construct as the endogenous. EFA was conducted separately on each instrument. Before conducting EFA there are several assumptions to be tested including the followings:

Sample Size: According to Zainudin [78], to run EFA a sample size of 100 to obtain the dimensions is needed. In the present paper, the sample size fulfill the minimum sample size required (n=102).

Adequacy of the EFA: was estimated through both (i) Kaiser-Meyer-Olkin measure of sampling adequacy (KMO). Hair *et al*. [37] suggested the acceptable value greater than 0.5 indicates that the variables have sufficient correlations. If the value is below 0.5, the variable should be dropped from the factor analysis. And (ii) the Bartletts test of sphericity to be significant. According to [68], Bartletts test of Sphericity should be significant (p value < 0.05) to represent that correlation between variables are large enough for factor analysis. Results of KMO and Bartletts test for both Soft TQM and LM are depicted in Tables 5 and 6, respectively. This was done after doing several iterations for each case.

Table 5 . KMO and Bartlett's Test for Soft TQM

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.807
Bartlett's Test of Sphericity	Approx. Chi-Square	375.516
	df	45
	Sig.	.000

Table 5 shows that KMO value for Soft TQM practices = 0.807 which is greater than the minimum level and indicates that it is an acceptable value. Furthermore, Bartlett's test was significant (p-value less than 0.05).

Table 6. KMO and Bartlett's Test for LM

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.779
Bartlett's Test of Sphericity	Approx. Chi-Square	1213.695
	df	325
	Sig.	.000

Table 6 shows that KMO value for LM practices = 0.779 is greater than the minimum level which indicates that it is an acceptable value. Furthermore, Bartlett's test was significant (p-value less than 0.05).

5.2.1. Extracted Success Factors

In the present paper, the number of factors extracted and retained for analysis was based on [37]'s recommendations that only factors that have eigenvalues more than 1 are considered significant. In addition, scree plots of the data set were utilized to determine the no. of extracted factors. Field [29] defined scree plot as a useful way of establishing how many factors should be retained in an analysis.

Factor extraction was conducted through Principal Component's Analysis (PCA) with varimax rotaton. PCA is a data reduction technique where the diagonal values of the correlation matrix, 1s, are used for the analysis to extract Maximum variance from the data set with each component thus reducing a large number of variables into smaller number of components [68]. Varimax rotation method is used in the present paper to minimize the number of variables that have high loadings on each factor and works to make small loadings even smaller [77]. It is the most common method in the orthogonal rotation.

First: Principal Component Analysis for Soft TQM (PCA)

Applying PCA through SPSS for 20 items for Soft TQM indicated that three factors have eigen values greater than 1 can be extracted. The final rotated component matrix resulted in 10 items, and the remaining items were discarded from further analysis as these have low communalities, cross loading issues, and low factor loading. This is presented in Table 7.

Table 7. Rotated component matrix for Soft TQM

Item No.	component 1	component 2	component 3
STQM3	.893		
STQM2	.841		
STQM4	.765		
STQM1	.709		
STQM9		.862	
STQM10		.754	
STQM8		.739	
STQM19			.821
STQM18			.770
STQM17			.713
Cronbach Alpha after EFA	**.844**	**.780**	**.705**
Cummulative Total variance Extracted %	39.291%	56.372%	68.734%

Based on Table 7, the factor loadings for all items are within the limits 0.709 and 0.893, which is considered among the acceptable range. The first factor comprises four items (ST 3, ST2, ST4, and ST1) while the second factor comprises three items, namely (ST 9, ST 10 and ST 8). The third factor also comprises three items (ST 19, ST 18 and ST 17). In addition, the values of crobach alpha after conducting PCA for the three factors are also still acceptable. The scree plot in Figure 2 indicates that there are three factors when the eigen value equals 1.

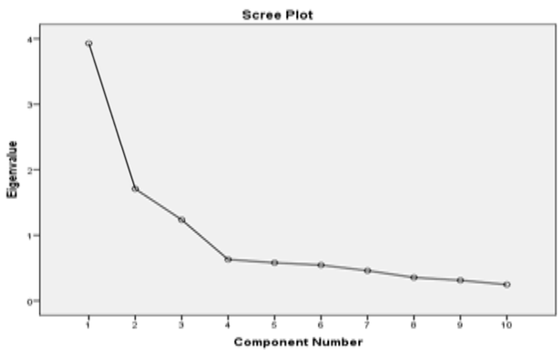

Figure 2. Scree plot for Soft TQM

Second: Principal Component Analysis for LM Practices (PCA)

In addition, applying PCA through SPSS for LM indicated that seven factors have eigen values greater than 1 can be extracted. The final rotated component matrix resulted in 26 items, and the remaining items were discarded from further analysis as these have low communalities, cross loading issues, and low factor loading. This is presented in Table 10

Table 10. Rotated Component Matrix for LM practices

	Component						
	1	2	3	4	5	6	7
LM57	.825						
LM56	.805						
LM58	.765						
LM55	.643						
LM3		.878					
LM2		.783					
LM4		.775					
LM1		.730					
LM27			.778				
LM28			.763				
LM26			.752				
LM24			.645				
LM38				.861			
LM39				.810			
LM37				.677			
LM36				.563			
LM17					.813		
LM12					.728		
LM13					.685		
LM14					.641		
LM20						.826	
LM19						.717	
LM21						.630	
LM31							.780
LM30							.751
LM33							.617
Cronbach Alpha	**.835**	**.839**	**.783**	**.863**	**.755**	**.703**	**.712**
Cummulative TVE %	24.162	39.224	46.395	53.035	58.876	63.663	68.199

Table 10 shows that factor loadings for all extracted factors range between 0.563 and 0.878 which considered an acceptable loading considering that the threshold is 0.55 [37]. Based on rotated component matrix, the first factor which is standardized work comprises four items, the second factor which is Just in Time (JIT) has four items. Factor three, namely workforce management, comprises four items; factor four also comprises four items and named as waste elimination. Factor five comprises four items and named as continuous flow. The last two factors each have three items. Factor six is TPM and factor seven is Kaizen. In addition, the cronbach alpha calculated for the extracted factors still acceptable. The scree plot in Figure 3 shows that there are seven factors based on eigen value which is 1.

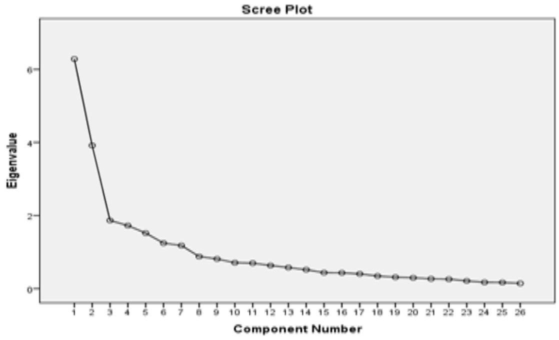

Figure 3. Scree plot for LM

6. Revised Model after EFA

After conducting PCA for both exogenous and endogenous latent constructs, extraction of factors for these initiatives will lead to develop the model based on Structural Equation Modeling. This is depicted in Figure 4. Investigation the hypotheses in this model will be among the future direction of the present paper.

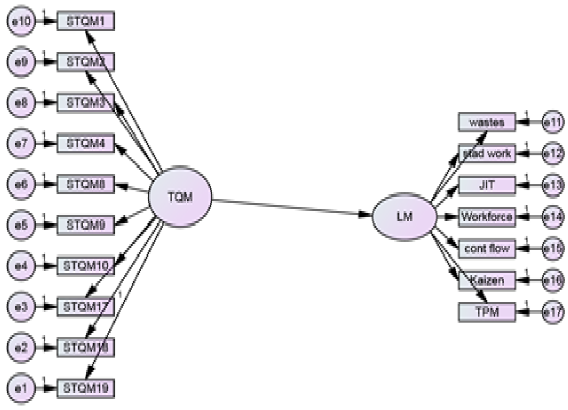

Figure 4. revised model after conducting PCA. Source: Authors computation

7. Discussion of Findings

The difference between the present paper and the other papers is linking both philosophies together in one multi-dimensional model and by investigating the most appropriate CSF for these practices. As per the results gained from SPSS 22 concerning factor extraction, seven factors were extracted for LM initiatives. These factors make this construct as multidimensional and saturated for implementation. It is considered as a guide for Malaysian manufacturers if properly practiced in the real world environment. This motivates Manufacturers to be leaner in 21st century in the Malaysian competitive market. Focusing on Lean wastes is among the top principles and aims of LM practice, this is also supported with Kaizen for incremental continuous improvement that manufacturers can observe in the production costs and perceived potential benefits and return on investment. Moreover, Just-in-time production also extracted as significant component which specifies that Malaysian managers ensure an awareness of this production policy which minimizes the costs of inventory availability and production style. These are coordinated with the continuous flow and classification of the products into groups and better improve the factory layout and minimize waiting time for material flow in an efficient manner. Moreover, Total Productive Maintenance (TPM) is also considered among the priorities of operations and quality managers in Malaysian industries as it is extracted also among the other components. This is concerned with focusing on maintaining equipment's regularly and efficiently. Standardized work aims to ensure that work processes are standardized. In addition, it is considered as a basis for the improvement in different aspects. It also implies that the managers and employees receive a standardized process instruction. All these are important factors that align with Toyota Production System (TPS) principles and concept. With reference to Soft TQM dimension, this is a new variable to be considered and integrated with the other practices QMS, EMS, LM and SP in the same integrated model that can enhance the strategic long term sustainable performance and logistics approach in the supply chain environment. Results obtained from PCA indicated that three different components are extracted and have the higher importance among others. These practices are described as follows: strategic planning component. In general, there is not a commonly accepted definition for strategic planning. [20] considers it as a component of strategic management. [13] defines strategic planning as "a deliberative, disciplined approach to producing fundamental decisions and actions that shape and guide what an organization (or other entity) is, what it does, and why". [20] argued that Strategic Planning is the initial stage and foundation of strategic management. Likewise, strategic quality management is among the major components of TQM. Human Resource Focus (HRF) is the second component. Human Resource (HR) focus is giving importance to employee in terms of providing opportunity to excel. Employees must be recognized for their achievements and equally rewarded to motivate them to perform better. Creating an environment where only merit gets berth. Training & development is an important activity which prepares the employee to respond effectively and efficiently towards changing business environment. Empowering employees is one of the most important aspects for building superior culture [27]. According to [20], Human Resources Management is the soft dimension of TQM. In TQM, providing employees with necessary training and ensuring the involvement of employees are necessities. The third component is Strategic quality policy. According to Yeh [76], strategic quality management is the process of establishing long range quality goals and defining continuous improvements to meet organizational goals, such as improving processes, products, and service.

7.1. Conclusions

The present paper proposes that both TQM and LM are not in conflict inside Malaysian manufacturing industries as TQM is a driver for LM tools and techniques. The similarities aspects between both employ that these have to be integrated together inside enterprises. Their synergy can enhance the performance in the competitive market. Thus, it is argued that these are available in the same enterprise. A cross sectional quantitative study was conducted to investigate the proposed model adapted from reliable and valid instruments. The present paper shows results of the preliminary study termed as pilot study. Using LM multidimensional construct in developing industry is relatively new which focuses on the advanced techniques that can enhance the environment inside enterprises. This present study has many benefits to the operations managers as it reflects a clear view about how LM can be defined and measured in the manufacturing industries. Utilizing the elements of Toyota production system can help build a better design for LM and enable the smooth implementation inside enterprises. Awareness of these tools, techniques and approaches mentioned in the present paper can reinforce enterprises in this competitive world. Thus, it is vital to adopt these systems and philosophies together to be integrated in the same environment as there are many elements in common and have the same priorities. Both reliability and descriptive statistics we estimated for the model constructs. Furthermore, with reference to EFA, results directed that Malaysian managers are involved with LM waste elimination techniques, such as workers motion, overproduction waste, reducing the excess inventory, and waiting waste. These are all extracted factors from principal component analysis. Furthermore, the employees recognize the importance of Kaizen aspects and initiatives for the continuous improvement.

Production and quality managers are strongly advised to follow up the continuous improvement journey on the long term perspectives. Both TQM and LM are viewed as long term strategic philosophies and the implementation of these can generate high customer satisfaction, reduction of wastes, defects, costs and improving the productivity and quality on the long run. This will ensure realization of better performance and sustainable environment.

7.2. Limitations and Suggestions for Future Research

Similar to other studies conducted in Operations Management, the present paper suffers from limitations which, at the same time, can be considered an agenda for researches and scholars to cope with in their new research. Among these is using the cross sectional approach. Other researchers may adopt the longitudinal design to study in depth these practices. In addition, it will be a good opportunity to compare the results among both the developing and developed countries. The present paper focuses on introducing the results of the pilot study; hence, authors believe that further research is needed to empirically investigate the model using techniques from Structural Equation Modeling. As the present paper focuses on measured manufacturing sector, we recommend making use of this study in the service sectors, such as healthcare, banks, and education sector since the practices implied can fit the different sectors on the long run.

Acknowledgements

Authors of the present paper are very grateful to the editor in chief, Prof. Dr. Ahmed Al-Ghandoor and the blind reviewers for useful comments and suggestions that improved this version of the paper.

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ISSN 1995-6665

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