DESIGN AND EVALUATION OF AN EDUCATIONAL GAME FOR ASSEMBLY LINE BALANCING USING LEAN CONCEPTS

(MONTAJ HATTI DENGELEME KONUSUNDA YALIN KAVRAMLARI KULLANAN BİR EĞİTSEL OYUNUN TASARIMI VE DEĞERLENDİRMESİ)

by

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LIST OF ABBREVIATIONS

ALB	assembly line balancing
KPI	key performance indicators
OPF	one piece flow
PDCA	plan, do, check, act
PW	positional weight
P1	phase 1
P2	phase 2
P3	phase 3
RPW	ranked positional weight
SALBP	simple assembly line balancing problems
TPD	technological precedence diagram
TQM	total quality management
WIP	work in process
5W-1H	where, when, who, what, which and who
5S	sort, straighten, shine, standardize, sustain

LIST OF SYMBOLS

CT	cycle time (time it takes to go through all work elements before repeating them)
LT	lead time (time it takes one piece to move through a process from start to finish)
TT	takt time (the available production time divided by customer demand)
H_0	null hypothesis
H_1	alternative hypothesis
μ_1	mean value of first sample
μ_2	mean value of second sample
α	confidence interval
$\bar{d}$	mean population difference
CV	coefficient of variations
s_d	standard deviation
$s_{\bar{d}}$	standard error of mean difference
R^2	correlation coefficient
n	number of sample
$\sigma_{C/T}$	standard deviation of cycle time
CT_{LR}	slope of regression line
n_s	number of stations
i	product no.
LT_i	lead time of related product
QPT	labor time per quality product

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ABSTRACT

The activities that aim to increase the productivity of assembly lines are among the very important activities in factories and they are considered as the origin of Industrial Engineering. Lean Thinking, coming from Toyota Production System was born with studies increasing productivity of assembly lines. Assembly line balancing activities are called as Yamazumi activities in Lean Thinking. These are not only important for increasing productivity but also critical for creating a sustainable culture for productive companies.

This study develops an educational game on assembly line design using lean concepts. The game uses the experiential learning technique, which is an effective tool that make the participants learn the assembly line design by experiencing working on an assembly line in an entertaining atmosphere. The game aims to show the participants that using lean techniques improves the line efficiency. LEGO® parts are used as educational material to simulate the assembly process of a selected product.

This educational game has three phases: in Phase 1, the participants assemble the entire product individually to get used to doing assembly operations; in Phase 2, working as a team, they design an assembly line with workstations that ideally have equal workload, while in Phase 3, they are introduced to lean concepts and then they are allowed to redesign the line. Using the assembly lines designed in phases 2 and 3 a number of products are assembled, and key performance indicators are compared to see the lean effect on line efficiency. This game has been played by several teams from different manufacturing sectors. A statistical analysis of the results shows that the performance of the simulated assembly lines has improved after applying the lean techniques.

Keywords: Assembly line balancing, lean thinking, lean methodology, yamazumi, experiential learning, educational game

RESUME

Les activités qui visent à augmenter la productivité des lignes de montage sont parmi les activités les plus importants dans les usines et elles sont considérées comme l'origine du génie industriel. La pensée *lean*, venant du système de production de Toyota, est née avec des études augmentant la productivité des lignes de montage. Les activités d'équilibrage de ligne de montage sont appelées les activités Yamazumi dans la pensés lean. Celles-ci ne sont pas importantes seulement pour augmenter la productivité mais aussi elles sont critiques pour créer une culture durable pour les entreprises productives.

On propose un jeu éducatif sur le design des lignes de montage en utilisant des concepts lean. Le jeu utilise un modèle d'apprentissage expérientiel, qui est un outil efficace qui font les participants apprendre par l'expérience et en se divertissant. Le jeu a pour but de montrer aux participants que l'utilisation des techniques lean améliorent l'efficacité de la ligne de montage. Des pièces LEGO® sont utilisées comme matériel didactique pour simuler le processus de montage d'un produit choisi. Le jeu a trois phases : Dans la phase 1, les participants font le montage entier du produit par eux-mêmes pour être habitués faire les opérations de montage ; dans la phase 2, travaillant en équipe, ils conçoivent une ligne de montage avec de postes de travails qui ont une charge de travail plus ou moins égale, tandis que dans la phase 3, ils sont présentés les concepts lean et ils sont donnés la chance de concevoir la ligne encore une fois. Utilisant les lignes de montages conçus dans les phases 2 et 3, un certain nombre de produits sont assemblés et les indicateurs de performance clés sont comparés afin de voir l'effet lean sur l'efficacité de la ligne. Ce jeu a été joué par plusieurs équipes venant de différents secteurs de fabrication. Une analyse statistique des résultats indiquent que la performance des lignes de montage simulées s'est améliorée après appliquer les techniques lean.

Mots-clés: l'équilibrage de la ligne de montage, la pensée lean, la méthodologie lean, yamazumi, apprentissage expérientiel, jeu éducatif

ÖZET

Montaj hatları ve montaj hatlarındaki üretkenlik artırma çalışmaları fabrikaların en önemli aktivitelerinden ve endüstri mühendislğinin merkezi konularından biridir. Toyota Üretim Sisteminden gelen Yalın Düşünce montaj hatlarındaki üretkenlik artırma çalışmalarıyla doğmuştur. Yalın Düşünce'de Yamazumi olarak adlandırılan montaj hattı dengeleme çalışmaları sadece üretkenlik artırma faaliyetlerinde değil; buna ek olarak sürdürülebilir bir üretken şirket kültürü yaratmak için önemlidir. Sürdürülebilir şirket kültürünü yaratmada, insanları etkilemek ve sürekli gelişim aktivitelerini yürütmede eğitimler önemli rol oynar.Bu çalışma, insanları motive etmek ve uygulama öncesi onlara deneyim kazandırmak için deneyimsel öğrenme metodolojisini temel alan, Yalın Kavramlar kullanarak tasarlanmış bir montaj hattı üzerinden kurgulanmış bir eğitici oyun tasarımı önermektedir.

Bu oyun, katılımcılara Yalın Kavramları kullanmanın hat verimliliğini iyileştirdiğini göstermeyi amaçlamaktadır. Örnek ürün üzerinden bir montaj sürecini simüle etmek için LEGO® parçaları kullanılmıştır. Bu eğitsel oyun üç aşamadan meydana gelmektedir: Birinci aşamada katılımcılar montaj operasyonlarını öğrenmek için tüm ürünü ayrı ayrı kendi başlarına montajlarken; ikinci aşamada bir takım olarak çalışarak eş iş yüküne sahip ideal bir montaj hattı tasarlamaya çalışırlar, üçüncü aşamada ise Yalın Kavramlarla tanışan katılımcılar, montaj hattını öğrendikleri bilgilere göre yeniden tasarlarlar. Hat verimliliğinde yalın tekniklerin etkisini ölçmek için ikinci ve üçüncü aşamada tasarlanmış montaj hatlarına ilişkin kilit performans göstergeleri karşılaştırılır. Bu oyun, farklı sektörden katılımcılardan oluşan birçok takıma oynatılmıştır. Sonuçların istatistiksel analizi, montaj hattında uygulanan yalın tekniklerin hat performansını iyileştirdiğini göstermiştir.

Anahtar Kelimeler: Montaj hattı dengeleme, yalın düşünce, yalın metodoloji,
yamazumi, deneyimsel öğrenme, eğitsel oyun

1. INTRODUCTION

Lean thinking is a way to eliminate wastes while stabilizing workflow and improving continuously. It is very popular in manufacturing, and it has been successfully implemented in a variety of sectors such as textile, automotive, food, chemistry etc.

Lean manufacturing leads to less costly and more flexible systems. Many tools of lean manufacturing are not used only for eliminating waste (such as unnecessary transportation, inventory, motion, waiting, over-processing, over-production and defects) but also for creating a strong organizational structure (Suzaki, 1988).

1.1 Importance of The Use Of Lean Methodology in Manufacturing

The aim of using lean concepts and tools is to create a system that is valuable, capable, adequate and flexible (Marchwinski, et al., 2008). Line balancing is one of the most important areas where lean concepts can create great value in manufacturing. Lean line balancing activities are called as Yamazumi in Toyota Production System.

1.2 Importance of Using Lean Concepts on Line Balancing

The pioneer of lean manufacturing is Toyota, which is an automobile manufacturer. The assembly activities form a major part of automobile manufacturing; hence, their efficient control is crucial for the success of manufacturing. The use of lean principles such as continuous improvement and respect for people can lead to assembly lines that are cost efficient and more productive and ergonomic (Liker, 2004).

Many lean concepts and tools are developed especially for assembly line activities such as error proofing Poka Yoke devices, production controlling Kanbans, ergonomic assessing Temotokas, light and sound warning Andon systems, line balancing Yamazumi Activities, etc (Bicheno, 2000).

All activities should be done using the two main principles of Toyota Way, which are "Respect for People" and "Continuous Improvement" (The Toyota Way, 2001). Cost reduction and flexible production environment are results of using these two principles. Today, productivity techniques and principles of Toyota are considered to be the best practices in the automotive industry (Womack et al., 1990). Not only automotive industry but also many other sectors, such as textile, food, FMCG (Fast Moving Consumer Goods), especially manufacturers having assembly lines in their production system, are successfully using the lean methodologies introduced by Toyota Production System (Womack and Jones, 1996).

1.3 Benefits of Use of Games for Education

Traditional or conventional training uses didactical methodologies and transfers knowledge by one side (Gagne, 1985). Traditional instructional design uses didactic learning methodologies strategically (Gagne, et al., 1988). An alternative way for training is the use of educational games. Training by games is considered to be an innovative way of inductive learning, which is learning by doing, discovering or inventing (Bruner, 1966, 1986). Using games in education is a more effective way of training than the traditional training (Amory and Seagram, 2003).

Learning is a process that is converging of grasping experience and transforming it (Kolb, 1984). "Scientists believe that educational games can unlock the students thinking and increase the feeling of fun while learning, therefore reduce the burden of delivered information given by the teachers" (Abu Raya, 2001).

1.4 Description of The Study

In this study, an educational game is developed for assembly line design using lean concepts, which we call Yamazumi Game. The aim is to show the participants that the use of lean approach increases the line efficiency. The game consists of three phases, each phase representing a different type of manufacturing system. The first is mass production just using interchangeable parts without an assembly line, the second is mass production with an assembly line that aims to maximize the production rate, and the last is mass production with a lean assembly line that aims to eliminate waste and improve quality by using lean concepts. In this phase, there are many concepts and techniques that are introduced to the participants based on;

- Five basic principles of Lean Thinking (Womack and Jones, 1996)
- Lean tools defined on Lean Turnaround (Byrne, 2011)
- Toyota Way (Liker, 2001) and Toyota Culture (Liker and Hoseus, 2007)

Using the assembly lines designed in phases 2 and 3 a number of products are assembled. Then, several game outputs and key performance indicators for the two phases are compared to see the lean effect on line efficiency. This game has been played by several teams from various manufacturing sectors. A statistical analysis of the results is done to compare the performance of the simulated assembly lines before and after applying the lean techniques.

1.5 Organization of The Thesis

Chapter 2 presents a brief literature review on the fundamentals of lean methodology, which is one of the most popular management techniques. Literature survey includes as well the studies on assembly line balancing with a special focus given to the lean techniques proposed for assembly lines that were initially used by Toyota in 1950s (Ohno, 1988). The last section of the literature survey is regarding studies on experiential learning methodologies and specifically on educational games.

Chapter 3 presents the educational game developed for assembly line design using lean concepts. First, the lean principles used in the game are introduced, then the educational materials are presented, and finally, the different phases of the educational game are described.

Chapter 4 presents the numerical study performed to evaluate the performance improvement effect of the lean techniques. The value of using lean concepts in assembly line balancing is evaluated through a statistical analysis done using key performance indicators collected from 12 teams formed by 80 participants from different sectors.

2. LITERATURE SURVEY

Lean thinking is first applied in the manufacturing sector in 1990s. Because of its success, it is later applied to other sectors as well such as healthcare, agriculture and construction (Marodin and Tarcisio, 2013). Primary purpose of Lean Thinking is to increase value adding activities from placing the order to the delivery of the order.

2.1 Fundamentals of Lean Methodology

The origin of lean thinking comes from Toyota Motor Manufacturing (Womack, et al., 1990). “A Lean Company” reduces costs significantly and produces world class quality more than a non-lean manufacturing company. Before Toyota started to use the Total Quality Management (TQM) techniques, their quality levels and customer satisfaction rates were not as good as those of American Automobile Industries in 1950s (Shimokawa and Takahiro, 2007). After adapting TQM tools to their manufacturing environment and improve their system using Just In Time concepts introduced in 1929 by Kiichiro Toyoda, their sales numbers started to increase year by year.

Taiichi Ohno who is the legendary engineer of Toyota Motor Co. created a system called as Toyota Production System (Ohno, 1988) where the just-in-time concepts are applied. The keystones of Toyota Production System are built using the popular lean concepts such as the concept of Standard Work, Kaizen, Poka Yoke, Visual Management, 5S, Kanban etc.

The main characteristic of Toyota Production System or Lean is to create a flexible production system that can produce a variety of products. Producing in large lots is believed to bring much less profit than the customized production in recent years (Jack, 2013). In Toyota production system and lean philosophy, the production lots are as small as possible in order to have an efficient production system. To enhance a flexible system, production lines have to be set up in very short times (Smalley, 2013).

A lean system is created considering five basic principles: Define Value from customer side, identify all phases in value stream, flow the production with minimum waste, pull the value from the next upstream activity, sustain continuous improvement until a state of perfection that can never be reached (Womack and Jones 1996).

2.2 Line Balancing and Assembly Lines

Originally, assembly lines were developed for a cost efficient mass production of standardized products, designed to exploit a high specialization of labor and the associated learning effects (Boysen et al., 2006). The assembly line can be described as a flow-based systematic production system that consists of workstations that are placed in series. A job that is completed in one workstation moves to the next until the complete assembly is obtained. In 1920s when the first assembly line was implemented in Ford, there was a single model black car called as Model-T runs on this assembly line. Henry Ford and Frederick Taylor dramatically changed the production way in automotive industry by dividing the production jobs into smaller tasks done by non-educated employers (Shtub and Dar-El, 1989). Not only separation of tasks into small pieces but also assigning these separated tasks to employers is the key success of Ford's assembly lines (Ford, 1926).

However, year by year, especially after World War II, consumer habits started to change. Thus, product variety has increased, which necessitated the customization of assembly lines (Jack, 2013).

The assembly line balancing (ALB) problems have been well studied in the literature. The first mathematical model of assembly line balancing was for assigning tasks to the workstations (Salveson, 1955). An assembly line is formed by workstations and certain tasks to be performed by each workstation according to a cycle time or takt time in lean companies (Boysen, 2006).

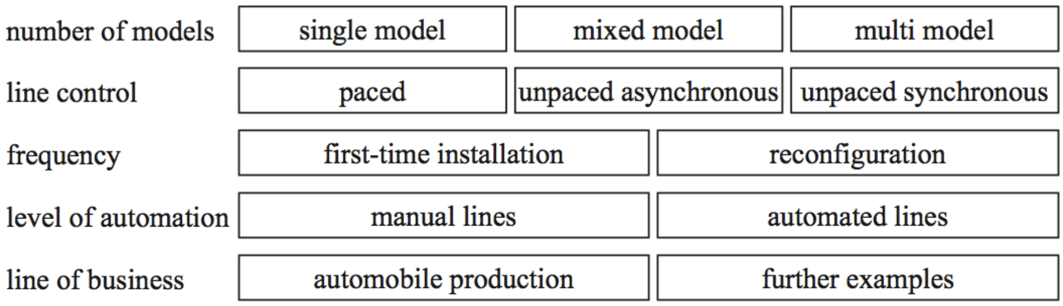


Figure 2.1 : Classification of Assembly Lines (Boysen, 2006)

The assembly line balancing problems can be classified into 12 types according to the number of models, line control, frequency, level of automation and line of business as explained in Figure 2.1 (Boysen, 2006). Assembly line balancing problems can also be classified into two main categories as single and general line balancing problems, which are further divided into sub categories (see Figure 2.2) (Ghosh and Gagnon, 1989).

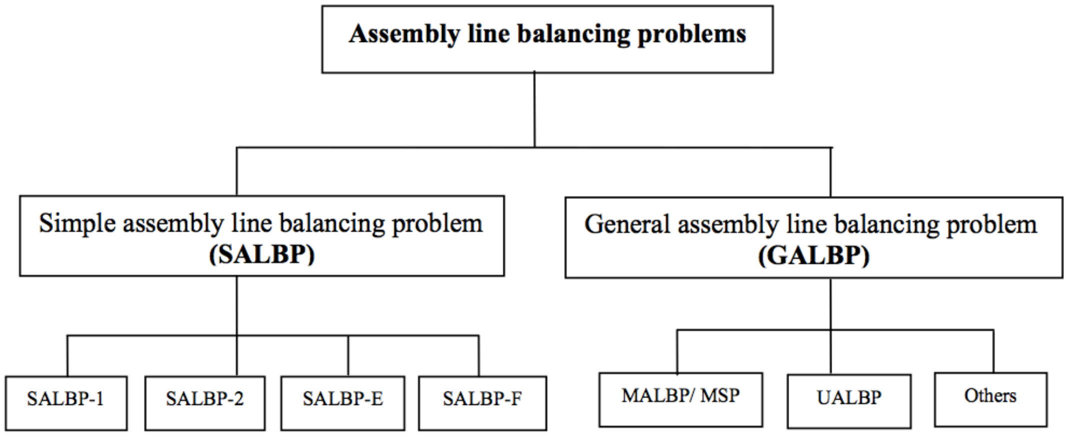


Figure 2.2 : Classification of Assembly Line Balancing Problems (Ghosh and Gagnon, 1989)

The basic problem of assembly line balancing is known as simple assembly line balancing problem (SALBP) (Baybars, 1986). SALBP can have different objectives. SALBP-E maximizes line efficiency while SALBP-1 minimizes the number of stations used in assembly lines considering a given cycle time. SALBP-2 is also maximizing line efficiency by changing the cycle time based on a given number of stations. The last

SALBP model called as SALBP-F finds a feasible solution when the number of stations and the cycle time are both given (Scholl and Becker, 2006).

In this study, we design an educational game on assembly line balancing where we specifically consider SALBP-1 and SALBP-2.

2.3 Lean Methodology and Line Balancing

Lean system is created considering five basic principles (Womack and Jones, 1996):

1. Specify value from the standpoint of the end customer by product family.
2. Identify all the steps in the value stream for each product family, eliminating the steps that do not create any value.
3. Make the value-creating steps occur in tight sequence so that the product will flow smoothly toward the customer.
4. As flow is introduced, let customers pull value from the next upstream activity.
5. Repeat lean principles 1-4, until a state of perfection is reached in which perfect value is created with no waste.

Toyota production system was created considering the following four principles (Smalley, 2004):

1. Setting and maintaining standards of tasks and jobs,
2. Solving daily problems that occur on line
3. Participating to the kaizen workshops (continuous improvement processes)
4. Organizing an efficient team work on assembly lines

According to Liker (2004), the Toyota Way considers the following principles:

- Long-term philosophy,
- The right process will produce the right results,
- Add value to the organization by developing your people, and
- Continuously solving root problems drives organizational learning.

All of these principles come from Toyota Assembly Shops. Because, the most employee-oriented part of automobile factories is Assembly Shops. Many of these principles served as inspiration for the Yamazumi Game, which is developed in this thesis.

‘Creating continuous flow and one piece-flow’ principle, that is used for clarification of problems on assembly lines, is a lean thinking philosophy and it is one of the various management principles of Toyota Way (Liker and Franz, 2011). Pull systems have a similar principle for eliminating waste and they are used in Toyota assembly lines. Assembly lines are stopped when a problem occurs in order to fix the problem to create the best quality. All tasks are standardized and visualized to improve continuously and clarify the problems.

Growing leaders is another philosophy of sustainable continuously improving assembly lines. Leadership hierarchy consists of a team leader, chief leader and group leader. This hierarchic organization is necessary for establishing channel to transfer knowledge from new members to experienced professionals. This teamwork atmosphere is one of the most effective strengths of Toyota and Lean Philosophy (Spear, 2004).

In Japanese Language, “yama” means mountain and “zumi” means leveling. Thus, Yamazumi activities focus on leveling of unbalanced tasks on assembly lines (Patchong, 2013). Nevertheless, Yamazumi is not only about line balancing. All of line balancing activities is named as Yamazumi including time studies and measurements, organization of ergonomic studies, assigning tasks to the stations and creating a team leader from team members etc. in Lean Methodology (Rother and Harris, 2001).

2.4 Fundamentals of Experiential Learning

Educational games are used to supplement the traditional teaching methods and they are applied in various areas (Costantino, et al., 2012). Educational games allow experiential learning that is defined as a combination of experience and reflections (Fowler, 2007).

According to Kolb’s experiential learning theory, learning is a progressive process from grasping experience to transforming it (Kolb, 1984). Educational games are used to develop emotional understandings using *learning by doing* methodology. Communication of people coming from different backgrounds and culture makes sharing experience more possible. Not only the experience shared by participants but also team working effect of experiential learning is the other reason of why educational games are more successful than the traditional teaching techniques (Pasin, et al., 2010).

Educational games are used in different sectors such as nursing, business management and medicine (Costantino, 2012). Operations management is one of these areas, because it is hard to understand theoretical concepts in operations management. Although theoretical basement is understood by students, they may fail to use this knowledge in practice. Awareness of theoretical knowledge can not be combined with practical experience in a classroom atmosphere (Ammar, et al., 1999). Educational games are important to create this combination.

Experiential learning concept can be described as a four-stage model involving four different learning models created with respect to the learning processes, types of knowledge and change processes (see Table 2.1) (Dieleman, et al., 2006).

Table 2.1 : Relationships Among Learning Processes, Types of Knowledge and Change Processes (Dieleman, et al., 2006)

Learning Process	**Type of Knowledge**	**Change Process**
Apprehension / Intension	Assimilative	Adapt to existing contexts
Comprehension / Intension	Accommodative	Adapt to different contexts
Comprehension / Extension	Convergent	Change within contexts
Apprehension / Extension	Divergent	Changes contexts

Experiential learning theory has four phases as shown in Figure 2.3. These four phases are concrete experiences, reflective observations, abstract conceptualization, active experimentation (Kolb et al., 1999).

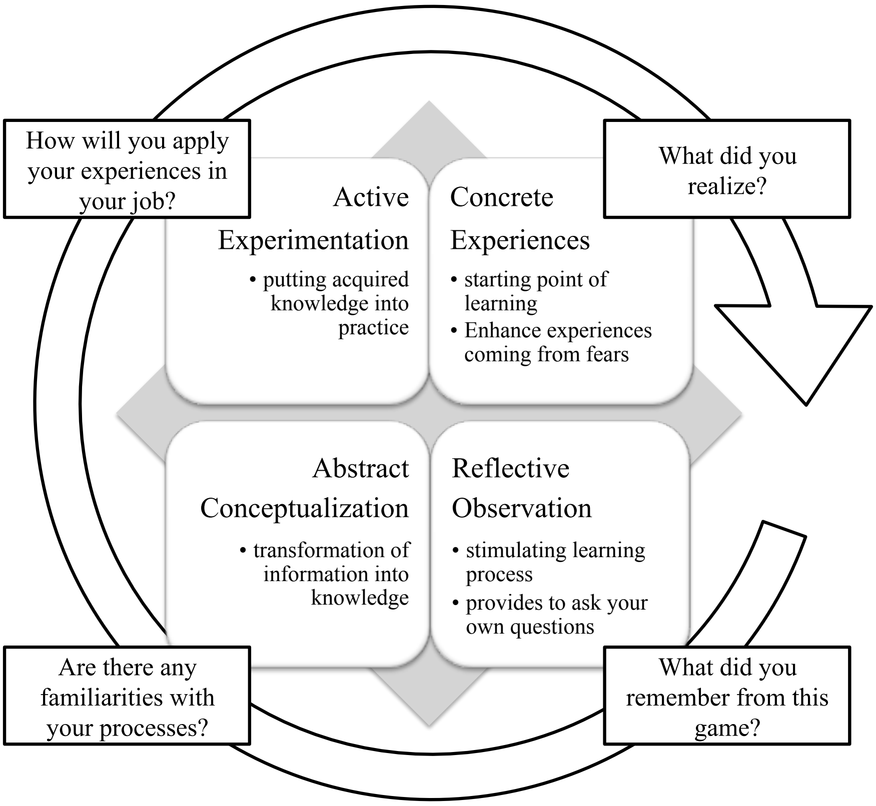


Figure 2.3 : The Experiential Learning Cycle of Kolb

Concrete experiences figure out experiences coming from fears. That is the starting point of learning. Question of "What did you realize?" is asked to the participants. Reflective observation phase is stimulating learning process and provides participants to ask their own questions to find familiarities with the processes in their own working environment. Abstract conceptualization transforms information to the knowledge and questions what the participants remember from this game. The last phase of learning cycle is active experimentation putting acquired knowledge into practice. How they apply their experiences into their jobs is asked to the participants.

Educational game is a way of experiential learning methodology by creating teamwork between participants and sustaining synergy during the training. It also changes paradigm of people who come from different sectors, different backgrounds.

2.5 Evaluation of Experiential Learning

Studies that present educational games found in the literature either use some performance outputs from game results (Ammar and Wright, 1999; Goldratt and Cox, 1992) or apply surveys to evaluate the participant satisfaction (Ranchhod et al., 2013). Scientists believe that educational games can unlock the students thinking and make the learning enjoyable and entertaining, therefore reduce the burden of delivered information given by the teachers.

There are many examples of educational games used in operation management education (Pendegraft, 1997; Jackson, 1996). In this study, different from most educational games presented in the literature, we design a multi-phase game on assembly line design that uses experiential learning techniques and aims that the participants experience the improvement effect of using lean methodologies. The game outputs are used to compare the performance between phases and statistical analyses by using KPIs (Key Performance Indicators) coming from different phases of the game are done to test if there is significant performance improvement before and after applying lean techniques. Details of game outputs, key performance indicators and statistical analysis will be explained in Section 4.

3. DESIGN OF THE EDUCATIONAL GAME

In this section we develop an educational game that we call Yamazumi Game, which is an experiential learning tool that aims to show the participants how the use of lean concepts in assembly line balancing can improve the line efficiency.

One of the most important missions of Yamazumi Game is to enhance the experience of Lean Methodology to the participants. Lean Methodology can be briefly described as a problem solving way and continuous improvement philosophy (Liker and Franz, 2011). In order to design a lean assembly line, the ***five basic principles of Lean Methodology*** need to be considered (Womack and Jones, 1996). The five basic principles are the milestones for designing the line, however some additional lean concepts as well are needed for an assembly line to work efficiently. Furthermore, the ***team leader and teamwork structure*** of Lean Methodology, which are successfully used in the assembly lines of Toyota Production System, are as important as lean concepts.

Yamazumi Game aims to teach the participants not only the main lean principles but also the other critical lean concepts and the teamwork structure of Toyota Production Systems.

3.1 Integration of Five Basic Lean Principles into the Game

Yamazumi Game is designed based on the five basic lean principles of lean methodology (Womack and Jones, 1996).

The first principle of lean is to ***define the value*** that the customers want (Womack and Jones, 1996). Built-in-quality provides the operator the ability of stopping the production in order to prevent producing defective products that are difficult to fix after the entire assembly is obtained. **Built-In-Quality** concept is integrated to the game design as it is done in Toyota (Toyota, 2010).

The second lean principle is **Value Stream**. Value Stream in the context of assembly lines refers to analyzing the wastes created in the assembly line and the value creation points (Ohno, 1988). According to the inventor of Toyota Production System, the value creation points could be detected on assembly lines. Work Study is the way of figuring out waste and value. Hence, work study elements should be integrated into Yamazumi Game.

The third principle is **Flow**. After detecting wastes that add cost but not value to the product and the value creation points that are reflected in its selling price, it is important to eliminate those wastes and increase the percentage of value creation points to create continuous flow (Rother and Shook, 1998). Thus, **value creation points and work load sharing** is one of the most important characteristics of the game (Rother and Harris, 2001).

The fourth lean principle is the **Pull** principle. Although the value defined by the customer, is created by the producer, it has to be delivered when the customer wants it (Liker, 2004). It is obvious from the above that **synchronizing production speed with the customer demand** is critical for the success of Lean Assembly Lines (Smalley, 2004).

The fifth lean principle to be considered in the design of lean assembly lines is the never ending improvement methodology called as **Perfection.** Even if all of these four methodologies previously mentioned could be used in assembly lines, it can never improve continuously (Womack and Jones, 1996). Hence, PDCA (Plan-Do-Check-Act) methodology (Deming, 1989) should be implemented in the Yamazumi Game to sustain continuous improvement using Kaizen principles.

3.2 Integration of Lean Tools into the Game

In addition to five basic lean principles defined previously, lean tools are more critical for production area. Some of these lean tools are specifically used in assembly lines. As defined by Art Byrne (2013) in his book entitled Lean Turnaround, there are four lean fundamental tools.

The first critical fundamental tool is **Working to Takt time**. Takt time is calculated based on the rate of customer demand. If the takt time is met, that means the production is synchronized with the demand. Hence, the participants have to understand the concept of takt time, its importance and how to calculate it.

The second fundamental tool is **One Piece Flow (OPF) that means** producing and moving one unit of piece at a time. If producer does not work to the takt time, this may cause high rate of work-in-process (WIP). Thus, one piece flow is a critical concept like the takt time and it has to be taught to the participants for a better assembly design.

The third important tool is **Standard Work.** Aside from one piece flow, standardized work also guarantees a stabilized output rate of the assembly line and may lead to potential improvement. Therefore, the importance of the standardized work and being open minded to improve standardization by PDCA cycle should be told to the participants of the Yamazumi Game.

The last important fundamental tool is **Pull System**. According to a pull system, the production is done after the customer orders are placed. Pull system results in a production rate that is synchronized with the rate of the customer demand. Pull system is considered in the game.

Lean tools are not enough for creating culture. They need to be combined with lean principles to understand the stems of lean methodology. As a result, the conceptual design of Yamazumi Game is based on both lean principles and the fundamental lean tools.

3.3 Integration of Team Leader and Team Work Structure into the Game

Four fundamental lean concepts of Art Byrne could be established as a part of lean assembly line and these are also combined with five lean principles of Womack and Jones (Womack and Jones, 1996). Nevertheless, an ideal assembly line like the ones in Toyota production system should be operated by a team, which consists of a team leader and 5-7 team members (Liker and Meier, 2005).

The most important advantage of a team leader who is working on an assembly line is to cover planned/unplanned absences of operators on the line (Liker and Meier, 2005). In case of any operator absenteeism, the assembly line can continue to produce without interruption at the ideal rate by the help of a multi-skilled experienced team leader. Team leader can work on the line instead of a team member. Finally, the game emphasizes the necessity of a **multi-skilled team leader** and the use of **teamwork**.

However, helping the team members is not the only responsibility of a team leader. The team leader is also responsible for providing the stabilization of the production rate, establishment of continuous flow and sustaining standardized work conditions to synchronize the assembly line according to the takt time. Therefore, the team leader should not be scheduled to be fully utilized (Rother and Harris, 2001). Yamazumi game has a scenario where the team leader has a workload of 20-25% at his workstation.

In conclusion, Yamazumi game aims to show the participants the importance of understanding the five lean principles, designing the line using four lean fundamental tools and using a multi-skilled team leader for a stabilized workflow on the assembly line.

3.4 Selection of Educational Material

Yamazumi (line balancing activities) that includes calculations and technical specifications is one of the technical tools of lean methodology. However, other tools of lean methodology have a strong relationship with Yamazumi. Since Yamazumi is not only used for the assembly line balancing problem, but also it refers to the organization of the workers on the line and the selection of the team leader, Yamazumi game has to allow all aspects of line organization and educate participants phase by phase the lean concepts, which are previously defined. Besides this, the participants also learn simple techniques for assembly line balancing.

Experiential learning methodology is used in Yamazumi game. Participants experiences the positive effect of learn concepts by working on two different assembly lines designed with and without considering lean concepts.

3.5 Details of Choosing LEGO®

LEGO parts are used as educational material in many experiential learning games (Pendegraft, 1997; Sterman, 1992) because they are an inexpensive and effective way of creating a work atmosphere. Figure 3.1 shows example LEGO parts.

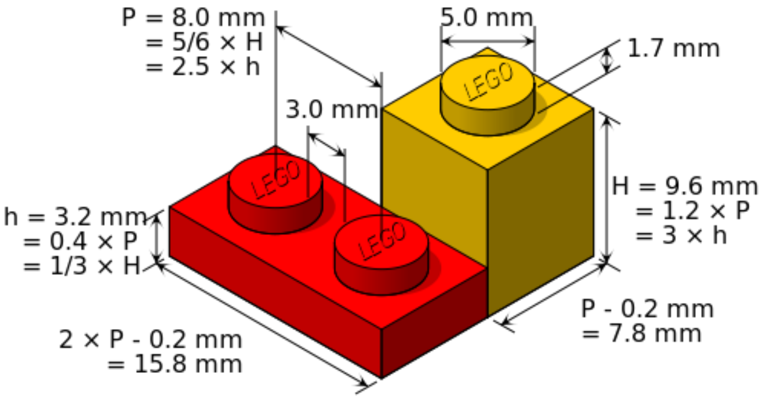


Figure 3.1 : Standard Dimension of LEGO Parts

LEGO® parts have many assembling advantages. All parts are standardized and it is easy to assemble and disassemble the parts. Because, all of the same parts of LEGO are interchangeable and standardized (LEGO Group, 2010). Standardized parts had also created a revolution in automobile production (Jack, 2013). In this way, the importance of standardized and interchangeable parts is emphasized.

The second important benefit of using LEGO® parts in Yamazumi Game is endurance of LEGO® parts. Interlocking plastic parts called as resilient plastic is extremely strong and having standard strong teeth that match with the holes when assembled (LEGO Group, 2010). Consequently, endurance of the parts provides long lifetime. In general, in each session of Yamazumi Game, every part of the product are assembled on average 3-4 times.

The last critical superiority of LEGO® is the ease of supply of the parts. In case of part losses or damages, it is easy to replace them with new parts. Based on our experience, after every five sessions of Yamazumi Game, around 5% of LEGO® parts are lost.

3.6 Details of Choosing Truck LEGO® 7630

The origin of assembly lines and assembly line balancing is the automotive sector. Dividing total workload into small tasks while producing cars moving on a conveyor belt is the brilliant idea of **Henry Ford** and his friend **Frederick W. Taylor** (Womack, et al., 1990). Hence, the automotive sector is the first sector that defined the rules of assembly lines.

The LEGO model 7630 (see Figure 3.2), which is a **medium wheel loader** model of LEGO® released in 2009 is selected for the game (LEGO Group, 2009). There are two main reasons of choosing the model 7630 over choosing a car model.

Figure 3.2 : Medium Whell Loader 7630

The first main advantage of choosing 7630 medium wheel loader instead of a car is having sub-assembled parts. These parts are cabin, backside, frontside, loader, rims-tyres and linkage that are independently assembled without precedence (LEGO Group, 2009) (see Figure 3.3). In brief, it can be said that this LEGO® model make possible to create a much more realistic assembly line.

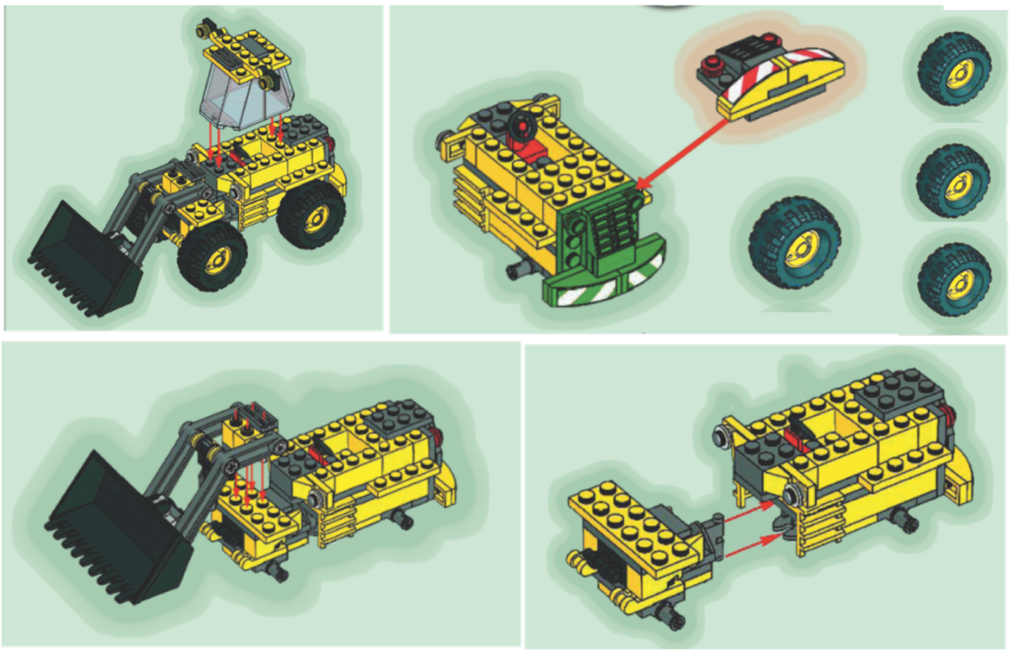


Figure 3.3 : Independent Parts (Front-Back Side, Cabin, Loader, Tyres)

Another important advantage of 7630 is that it has big tyres and rims and other medium and big parts. This feature creates an advantage of ease of assembling. Some of the participants are women and her hands are smaller than the male participants. Moreover, this anatomical feature of woman hand creates inequality between men and women when assembling small parts. Hence for ergonomic reasons, a LEGO Model that has big tyres and rims was appropriate to choose for this game.

3.7 Modification of Educational Materials

Ergonomic advantages and the dimensions of the parts of 7630 are the main reasons for choosing this model for Yamazumi Game. However, some parts of 7630 are not as ergonomic as other parts. The physical constraints of some parts have a handicap for assembling correctly and easily; therefore some parts are glued to each other to allow easier handling and assembly of parts (see Figure 3.4). Moreover, there are some rules for parts to be glued and modified.

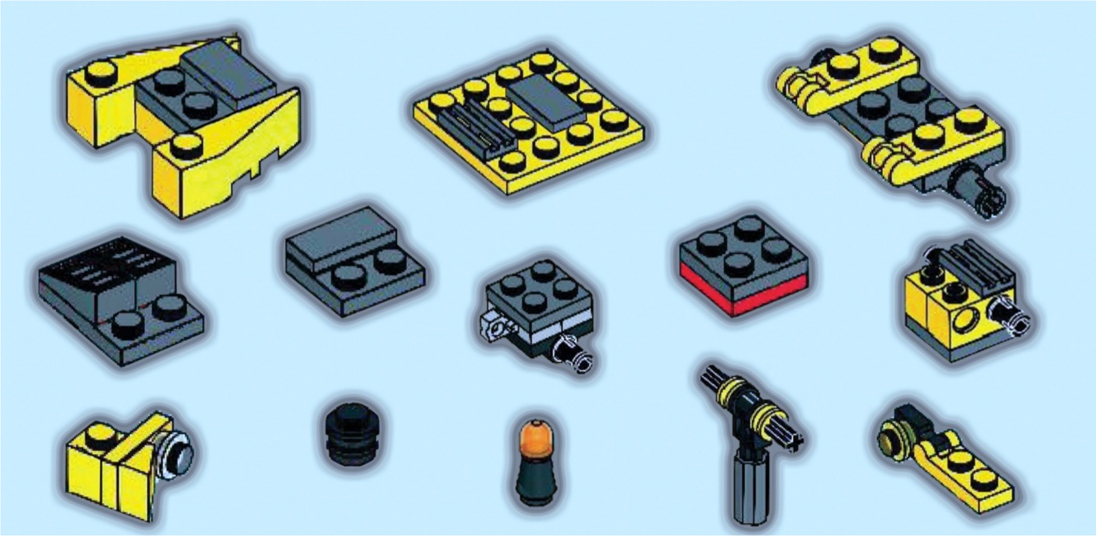


Figure 3.4 : Glued Parts of 7630

One of the rules of gluing parts is the dimension of the parts. Parts having less than three holes and teeth are selected to be glued to the related main parts (see Figure 3.5). In this way, some small parts are combined, which eliminated the risk of having non-ergonomic parts. The full list of glued parts can be found in Appendix A with modified instructional manuals.

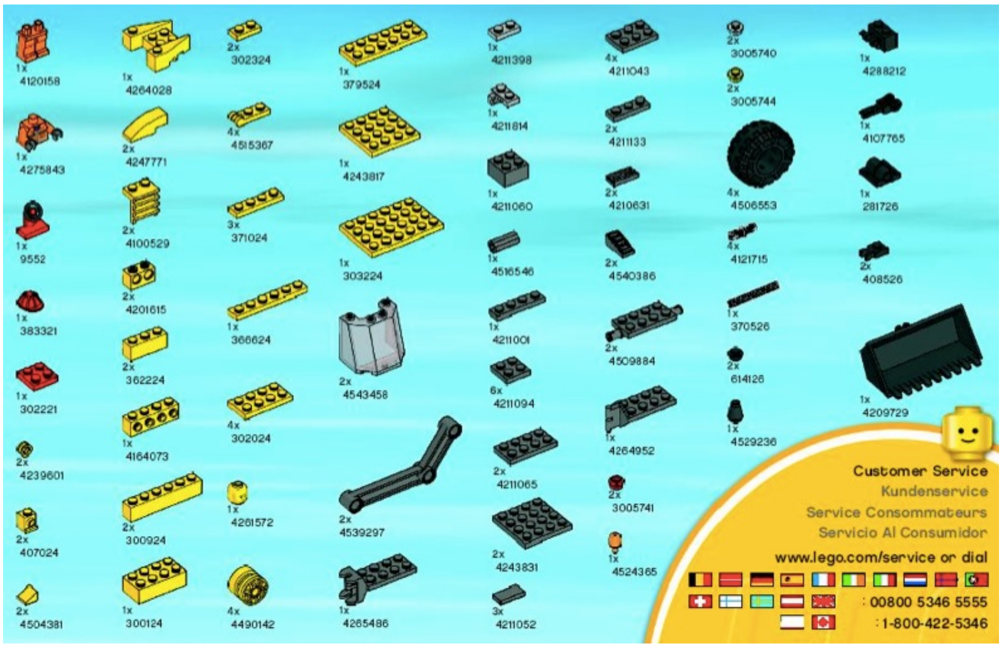


Figure 3.5 : 7630 Part List

Another reason for gluing the small parts is to reduce the risk of missing. Some parts of 7630 are transparent that can be easily missed. Thus, the parts that have not only less than three holes but that are also transparent are glued to prevent potential disappearing.

The last and the most important reason for gluing parts is the necessity of reducing number of stations on the assembly line. Model 7630 has over 80 parts, which requires over 80 assembly operations. Because the number or tasks are too many, for an efficient game performance, some parts of the model are glued and combined with each other to reduce the total number of parts to be assembled. Decreasing the number of assembly tasks (see Figure 3.6) and consequently the number of work stations provides an easier scenario for the participants.

In short, modification of the parts by gluing is done to avoid possible missing, to providing easy handling for the participants and to reduce the size of workload on the assembly line.

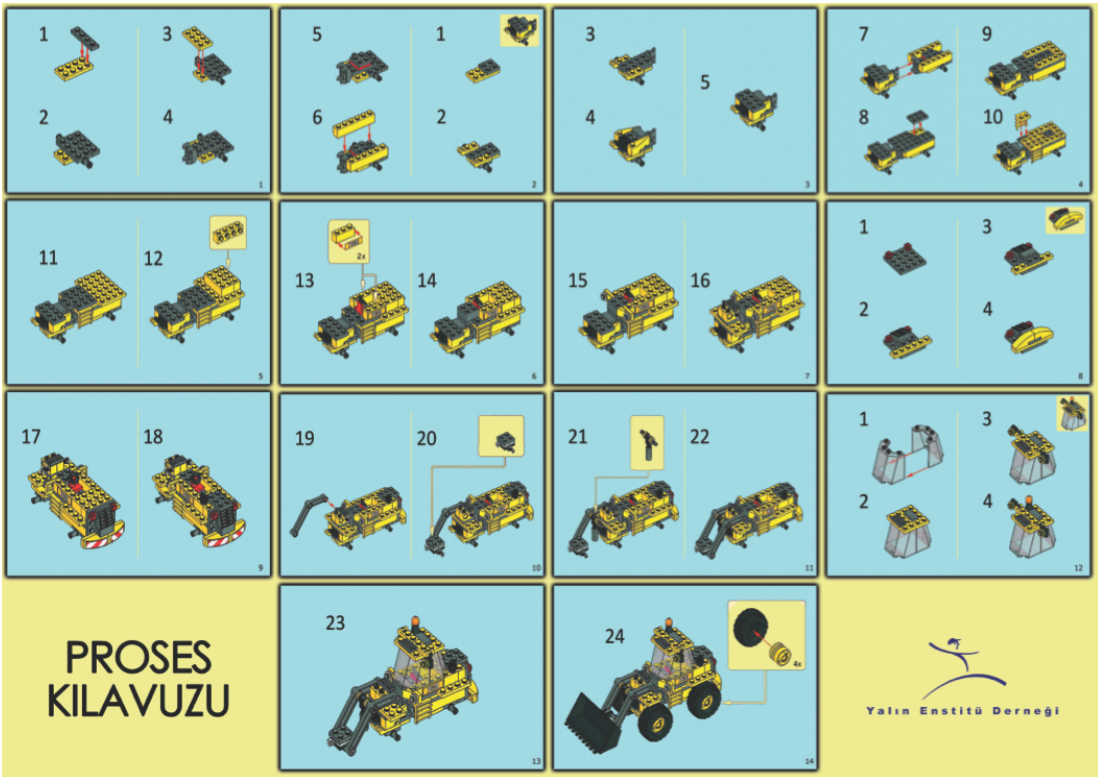


Figure 3.6 : Modified Instructions for Glued Parts

3.8 Description of the Educational Game Phases

Yamazumi Game aims to teach the participants how to do the line design using lean methodology. Yamazumi game uses experiential learning approach. For an effective knowledge transfer, the game consists of multiple phases where in each phase, the participants are provided different sets of instructions related to the assembly operations and lean tools and they are asked to work on the assembly of a product.

The game consists of three phases as shown in Figure 3.7, which are described in the following sections.

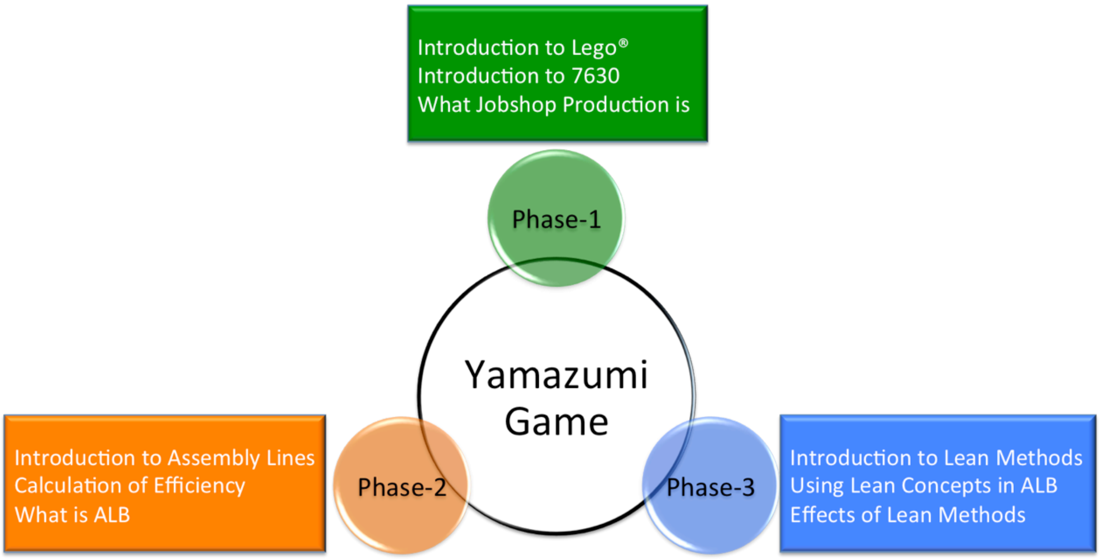


Figure 3.7 : Phases and Contents of Yamazumi Game

The maximum number of participants per game is restricted to 20 and the participants are grouped into teams that consist of up to 5 people in Phase 2 and Phase 3 for an effective learning.

3.8.1 Phase 1 (P1): Introduction to the Educational Material

In Phase 1, the participants are introduced the educational material. The participants are expected to learn how to assemble an entire LEGO toy product, specifically the LEGO model 7630 using its instruction's manual (See Appendix A).

Every participant works on their own to complete the assembly of one product. This session aims to teach the participants the mass production environment without assembly line and make them get used to assembling interchangeable LEGO parts.

A maximum of 30 minutes is given to the participants to work on the assembly of the LEGO toy, and the completion times by each participant are measured using chronometer. These completions times are not used for performance comparison purpose, but they are used to create in a fair way the teams with 4-5 members who will work in the subsequent phases of the game. Details regarding the classification of the participants into teams are described in Phase 2.

The importance of mass production and standardized parts is described and the positive effect of using standard parts and sharing tasks on the throughput time is discussed in order to prepare the participants for the next session.

3.8.2 Phase 2 (P2): Assembly Line Design Without Lean Concepts

This phase aims to make the participants understand the fundamentals of assembly lines and assembly line balancing.

In this phase, first the teams that will work on assembly lines are formed by taking into account the completion times of the participants from phase 1. The participants are ranked from the fastest to slowest, and they are distributed to the teams of 4-5 people in a balanced way in order to prevent an unfair assignment that may lead to too strong or too weak teams.

The assignment of the participants into teams is done as follows: Say there are 20 participants who have completed the assembly of model 7630. The participants are ranked from the best to the worst according to the completion times. The best and worst participants are picked to be in Team 1. Then, similarly, the second best and second worst participants, third best and third worst participants, and the fourth best and fourth worst participants are picked to be in Teams 2, 3 and 4, respectively. The remaining 12 people usually have completion times that have low variance and they can be distributed to the teams randomly. Distributing participants this way prevents unbalanced teams in terms of qualification. After the teams are formed, they are taught the fundamentals of assembly lines and line balancing and they are informed about the rules of Phase 2.

The first part of Phase 2 starts with information about the importance of assembly lines, the necessity of workload sharing and the importance of standard and repetitive work using standard parts, how Frederick Taylor minimizes throughput time (Taylor, 1911) with line balancing, what the cycle time is. Participants learn about mass production and history of assembly lines. Participants are warmed up with this information session for the application part of Phase 2. In the application part, the participants are informed about the goals of Phase 2.

The participants are provided information on the simple assembly line balancing problem (SALBP). In SALBP, tasks are assigned to workstations considering the technological precedence relations with the objective of either minimizing the number of workstations for a fixed cycle time/production rate (known as SALBP-1) or minimizing cycle time (i.e. maximizing production rate) for a given number of stations (known as SALBP-2) (Scholl and Becker, 2006). Designing a line using the SALBP-2 model is expected from participants in phase 2. Task time and customer demand information is not shared with the participants in phase 2. This leads to an intuitive workload assignment that is based on equally sharing the assembly operations, i.e. each participant selects a more or less equal number of tasks to perform at his/her workstation. For example, if there are 100 assembly operations to produce the LEGO Model 7630, each participant takes 20 assembly tasks to minimize cycle time, i.e. maximize output. However, this intuitive assignment does not balance workstation workloads properly. As in Phase 1, the participants use the instruction manuals to assign tasks to the workstations on the assembly line.

Phase 2 simulates an assembly line that is similar to the earliest Ford assembly lines in the 1910s that aim to maximize output without worrying about the quality defects. Thus, every worker has to work as fast as possible, ignoring quality defects and having no responsibility of downstream or upstream processes with the aim to minimize cycle time and maximize output rate (See Appendix B). The participants are not provided any information on the task times of model 7630. Hence, each team member tries to balance the line intuitively in Phase 2 by making the assumption that each assembly operation would take the same time.

Phase 2 ends with the measurements of the completion times of all products by the teams. The completion times will be used later for comparing the performance of the lines designed in Phases 2 and 3.

In short, Phase 2 of Yamazumi game makes the participants work together on an assembly line without worrying about the quality of the output.

3.8.3 Phase 3 Assembly Line Design with Lean Concepts

Phase 3 phase of Yamazumi Game aims to teach the participants who have understood the fundamentals of assembly line design in Phase 2, the assembly line design using the lean tools.

In phase 2, after learning the fundamentals of workload sharing and assembly line history, the participants balance the assembly line intuitively. They are not informed about the task times and customer demand. Hence, they just try to maximize the output while ignoring quality defects and work-in-process.

In phase 3, the participants are first taught the lean tools and techniques. The five basic principles of lean thinking (Womack and Jones, 1996) and four fundamental tools (Byrne, 2011) are defined and discussed with participants to create an awareness of how a lean assembly line has to be.

All participants watch a video called as “Toyota Production System” (Toyota UK, 2013) before discussing about the lean principles and lean tools. After watching three-minute video of Toyota assembly lines, the participants are asked to write three most effective moments of the video to a post-it. The discussion period starts with reading these most effective moments according to the participants and the participants are asked to talk about the lessons learned and the mistakes done in Phase 1.

After the discussion of video, 5W-1H (the first letters of what, which, when, where, who and how) (Matthews, 2011) period of 5 lean principles starts with asking participants the reflections of lean thinking on lean assembly lines. Discussion starts with **What** is the Value, which is the first principle of five basic lean principles and continues with **how** it can be used on assembly lines, defined by **which** tools on Lean Concepts, **when** and **where** it has to be used by **whom.** Discussion is continued with five basic principles of Lean Thinking. Hence, the lean tools that are used to design the lean assembly lines are introduced to the participants.

Discussion continues with how to integrate the lean tools into the assembly line, how to implement team work and team leader structure into the workplace. Other tools that are not discussed on video watching period like standard work, one piece flow, team work philosophy and team leader effect on the lean assembly lines are defined and evaluated to create a more productive and efficient assembly line.

After the discussion part ends, technical information session starts where the participants are taught how to calculate the takt time and the number of stations required in the assembly line, how the tasks will be assigned in case of excess capacity for a station. (See Appendix B).

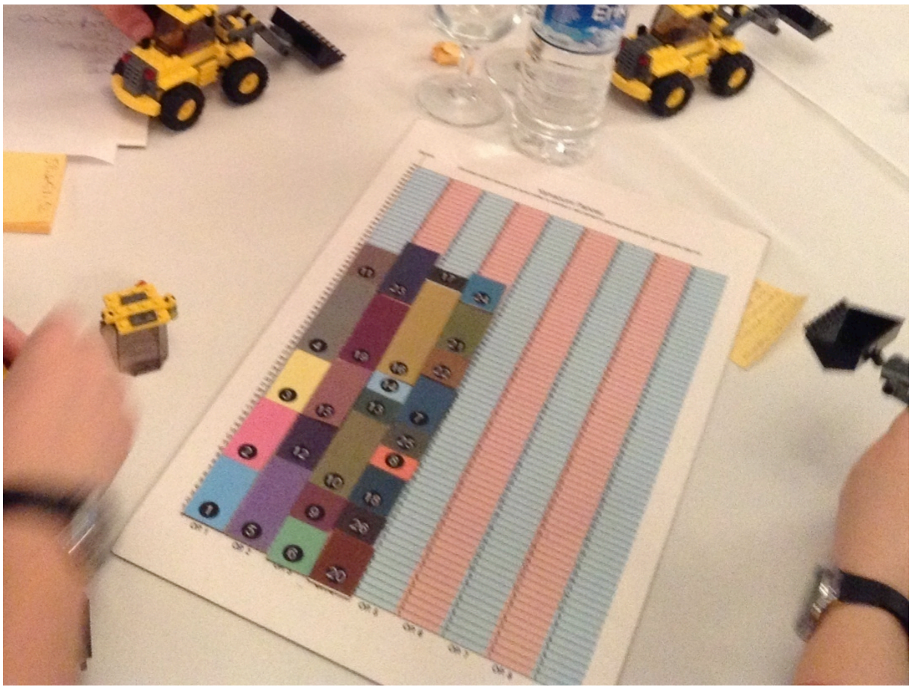


Figure 3.8 : Yamazumi Board Organization Session

At the Yamazumi Board Organization session (see Figure 3.8 and 3.9), the participants are informed about the production target based on customer demand, task predecessors and task times to calculate the total process time and the number of stations. In the Yamazumi Board Organization period, a **Technological Precedence Diagram (TPD)** exercise is used to teach participants what the precedence diagram is and the importance of TPD in task assignment (Abdulhasan, 2007). Yamazumi board organization session, calculation of number of stations and assignment of tasks could be explained in section 3.9.2 in detail.

After the information period, 30 minutes is given to the participants to assign the tasks and do the necessary calculations for SALBP-1 model (Baybars, 1986). The participants who have learned TPD methodology during Yamazumi Board Organization Session assign tasks into stations.

Figure 3.9 : Job Assignment on Yamazumi Board

Secondly, lean methodology implementation part starts and 30 minutes is given to the participants to implement the lean tools on the assembly line. Participants answer questions about which visual devices will be used to prevent quality defects and assembling mistakes, how sub-assembled parts and materials will be organized on the line, how one piece flow will be implemented on the line, how team leader works to compensate instabilizations, improve total efficiency of line and provide quality.

In Phase 3, one team leader is chosen among the team members to work on the lean assembly line.

Figure 3.10 : Lean Methodology Period and Line Organization

Third part of Phase 3 of Yamazumi game starts with line performance test by pilot production. Applicants try to produce only one product to be sure about workload sharing, material supplement, process details and prevent possible quality defects that may occur during assembling. After the trial production, team members disassemble their trial product and supply its parts to the corresponding stations (see Figure 3.10).

Finally, when all teams finish their pilot production, the competition period starts. All teams start the production simultaneously and the completion times for the products are measured by the chronometer. When a product is completed by each team, the time is recorded on a flipchart. The team that produces eight non-defective products in the shortest lead time while working on stabilized cycle time, wins Yamazumi Game. Phase 3 of Yamazumi Game ends with discussion and evaluation period of results and lessons learnt regarding the lean methodologies.

As a result, the third phase of Yamazumi Game aims to teach the participants the lean methodologies by using 5W-1H (the first letters of what, which, when, where, who and how) approach to create an efficient line balancing. Another advantage of Phase 3 is the combination of systematic thinking of industrial engineering according to SALBP-1 model for line balancing and the practical application of lean methodologies.

Progression between phase 2 and phase 3 is a continuous improvement cycle. Implementation of each phase includes the steps of discussion, information, evaluation, the trial production and the entire production. (see figure.3.11)

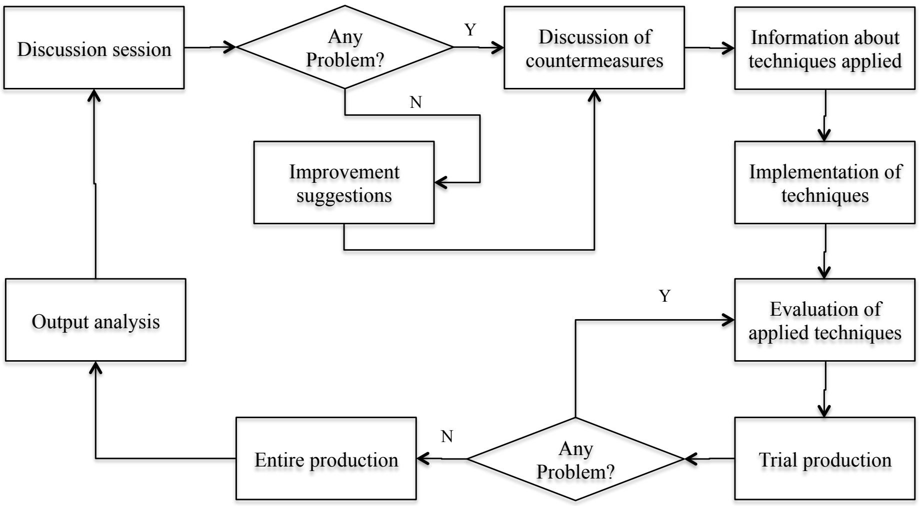


Figure 3.11 : Progression between Phase 2 and Phase 3

3.9 Concepts and Observations in Phase 2 and Phase 3

During the game, there are some concepts used to design the lines in phase-2 and phase-3. These concepts characterize the main features of assembly line concepts.

3.9.1 Concepts Used in Phase 2

After mass production without assembly line in phase 1, participants try to design a system that is similar to the Ford assembly lines in 1910s that aim to maximize output without worrying about the quality defects. There are three main principles used in phase 2 to produce 7630s.

3.9.1.1 Task Sharing Based on Number of Assembling Parts

Task time and customer information is not shared with the participants in Phase 2. This causes an intuitive workload assignment that is based on equally sharing the number of assembling parts. Thus, each participant shares the assembling operations. However, this intuitive assignment does not necessarily balance station workloads properly. Some teams uses parallel station layout to balance jobs. Unfortunately, they can not succeed to balance the line.

3.9.1.2 SALBP-2 Model

The assembling procedure applied in Phase 2 is an SALBP-2 model. For example, if there are 100 assembling operations of 7630 production, each participants take 20 assembling tasks to minimize cycle time and maximize output. SALBP-2 model does not use the customer demand information. The concern of the model is to maximize the production rate, not to synchronize the production with the demand.

3.9.1.3 Output Maximization

The SALBP-2 model does not synchronize the production with the customer demand. Thus, the production flow and the work in process (WIP) is not smooth through the production line. When we pause the production for a short time to observe WIP and line conditions, we observe that there are so many WIP and untidy work area conditions can be seen on the tables where the assembly line is constructed. Because each participant focuses on maximization of the output of their own station, this may lead to high WIP at some stations, especially when the assembly line is not properly balanced.

3.9.1.4 Poor Quality

The objective of output maximization may cause poor quality. Each participant tries to maximize their own production even if they produce defective or scrap parts. Nevertheless, it is observed that the percentage of quality parts depends on the teams and the rate ranges from 37.5% to 100%. Moreover, poor quality parts also affect production performance. One of the main reasons of cycle time fluctuations on assembly line is the time spent to fix problems on WIP and finished products.

3.9.2 Concepts Used in Phase 3

There are many Lean Concepts used in Lean Methodology. Some of them are commonly used for assembly lines. In Yamazumi Game we teach and apply various tools to improve the efficiency of the assembly line and make KPIs favourable. The techniques used are explained in the following sections.

3.9.2.1 Task Sharing Based on Time Studies (Yamazumi Board)

Participants use Yamazumi Boards to assign tasks to Takt Time. Premeasured task times symbolized with time columns are given to participants to fill the Yamazumi Board. Each column symbolizes the time of a task that is given in the instructions manual in Phases 1 and 2. Yamazumi board visualizes the workloads of each station and help the participants balance the line easily.

3.9.2.2 Precedence Diagrams and Positional Weights

Precedence diagrams (see Figure 3.12) visualize the precedence relations between tasks and indicates which operations should have higher priority. The use of precedence diagram not only prevents mistakes of assembling operations but also help participants to assign jobs properly.

Positional weights (PW) are calculated by using TPD (Technological Precedence Diagram) S(i) represents set of successors of tasks i, Task r represents a member of *S(i)* only if there exists an immediate successor relationship from *i* to *r*. t represents the task time. PW (positional weight) is calculated as follows;

$$PW_i = t_i + \sum_{r \in S(i)} t_r \tag{3.1}$$

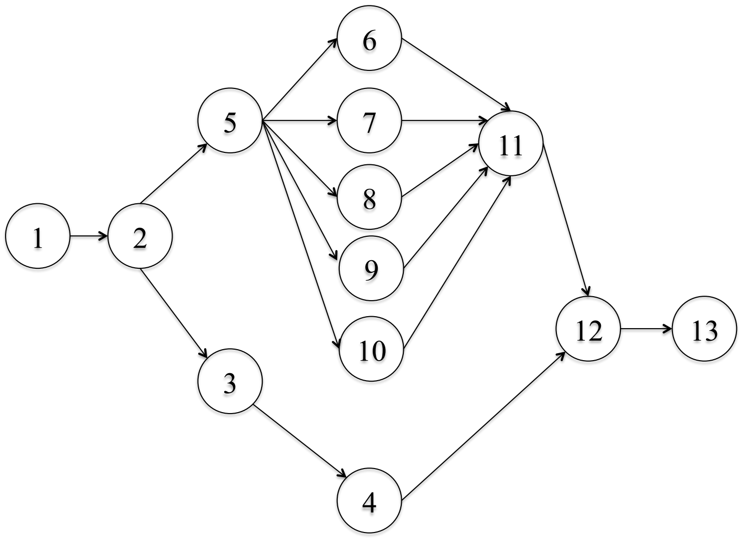


Figure 3.12 : TPD (Technological Precedence Diagram Example)

Positional Weights are calculated step by step using TPD and given task times on Table 3.1.

Table 3.1 : Calculated PW Values

Element	PW	Task Time	Predecessors
1	210	20	
2	190	20	1
5	115	7	2
3	106	45	2
8	75	20	5
9	70	15	5
7	63	8	5
4	61	10	4
6	60	5	5
10	60	5	5
11	55	4	6,7,8,9,10
12	51	45	4
13	6	6	11

3.9.2.3 SALBP-1 or Desired Cycle Time (Takt Time) Concept and RPW Algorithm

The set S_k includes the tasks assigned to station k. T_k represents the total workload of station *k*, which is calculated by simply summing the task times of all tasks assigned to station *k*, as follows.

$$T_k = \sum_{j \in S_k} t_j \tag{3.2}$$

The station times should not exceed the takt time *TT* (i.e. desired cycle time) ($T_k \leq TT$). According to SALBP-1, the takt time (desired cycle time) is given. The aim of the model is to maximize the utilization of stations.

The task having maximum positional weight is assigned to the first station as a first task; then this process continues until the capacity of first station is filled. When the first station is filled, the remaining tasks are assigned to station 2, then station 3, etc until all tasks are assigned. Participant use this approach to assign tasks to the desired stations.

RPW algorithm could be explained in detail as follows (Guhutukade and Sawand, 2013);

- Step 1: Draw the TPD
- Step 2: For each work element, determine the positional weight. It is the total time on the longest path from the beginning of operation to the last operation of the network.
- Step 3: Rank the work elements in descending order of ranked positional weight (RPW).
- Step 4: Assign the work element to a station. Choose the highest RPW element. Then, select the next one. Continue till cycle time is not violated. Follow the precedence constraints also.
- Step 5: Repeat step 4 till all operations are allotted to one station.

3.9.2.4 Team Leader Idle Time Maximization

In phase 3, the aim is to maximize the utilization of stations except the last station. The last station's workload is minimized in order for the team leader have the maximum idle time that he can use to fix any problem that may occur in the other workstations. This objective is equivalent to the minimization of the number of stations given a takt time, which is the objective of SALBP-1 model.

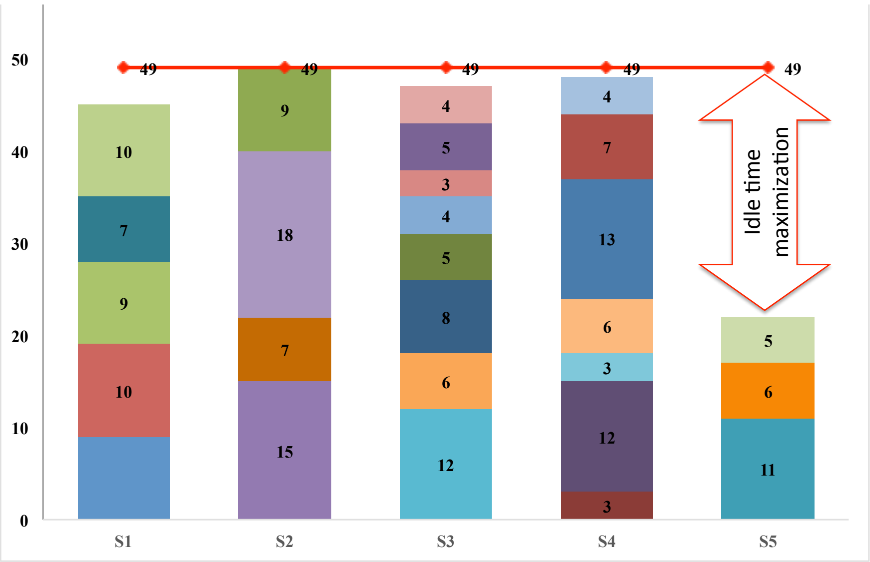


Figure 3.13 : Team Leader Concept and Idle Time

In figure 3.13, we see a situation where the utilization of the last station is minimized or equivalently the idle time of the operator at that station who act as the team leader is maximized. The team leader helps the other team members to finish their work within takt time (i.e. desired cycle time) at their workstation and prevent possible fluctuations on cycle time by fixing quality problems that may have occurred. In many game sessions performed, it is observed that setting the assembly line this way, i.e. with the last station being minimally loaded where the team leader has idle time to help others increase the performance rate of teams.

3.9.2.5 Continuous Improvement Activities

Continuous improvement activities are the keystone of the lean production systems that is required to achieve perfection. Every problem solving activity is called a continuous improvement activity. Participants try to solve many problems in order to design a perfect assembly line and each activity that improves a KPI serves for continuous improvement. For example, every time there is an improvement (i.e. a reduction) in task times, the total workload would reduce, which would eventually decrease the number of stations required on the assembly line. This way, the team leader at the last station who was originally responsible of doing some tasks at that station would become fully idle. Thus, the same production rate would be achieved with fewer operators, i.e. line efficiency would increase. In practical application, in such situation, the team leader is employed as a a continuous improvement chief. In Yamazumi game, it is observed that, all of the participants actively participate to the discussion about how to improve their lines, how to change the layout and how to perform better after phase 2.

3.9.2.6 Poka Yoke Markers

During some game sessions, it is observed that the participants marked the LEGO® parts in a way to prevent a potential assembling mistake, which improved the performance rate and decreased the number of defects. In practical life, mistake proofing activities that are called poka yoke are used in order to achieve zero defect target in production. Poka yoke devices are generally built from sensors, pneumatic circuits, and automation devices. Clearly, for this game, the participants did not use any complicated poka yoke device. They simply used a pen to mark the teeth of a LEGO part that will be attached to another part.

3.9.2.7 5S Activities

Some visual regulations are used to improve the line performance such as organization of stations, grouping of sub-assembled parts and WIPs, defining their locations, etc. (see figure 3.14). It is observed that this type of organization on the assembly line creates a much more efficient workplace and prevents the mistakes that may occur due to any clutter on the workplace.

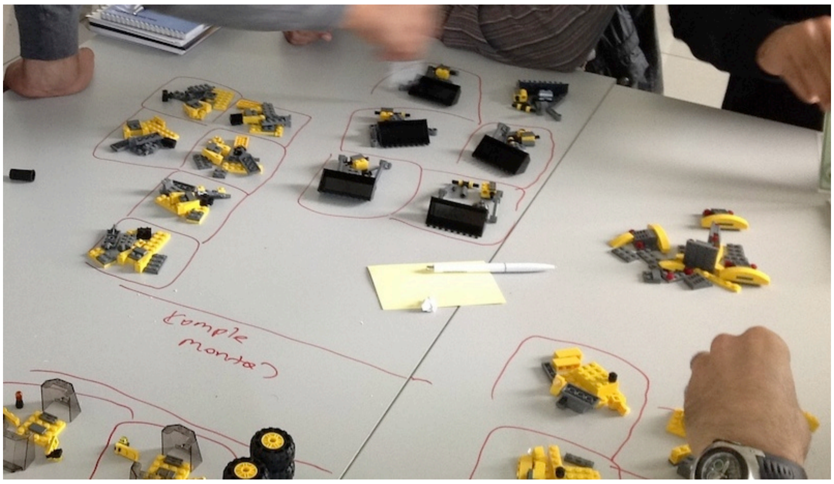


Figure 3.14 : 5S Activities on Desinged Line (Phase 3)

3.9.2.8 One Piece Flow (OPF) Concept

One piece flow (OPF) is one of the most critical concepts of lean assembly lines. It can be defined as "producing and moving one item at a time (or a small and consistent batch of items) through a series of processing steps as continuously as possible, with each step making just what is requested by the next step"(Marchwinski et al., 2008) (see figure 3.15).

Figure 3.15 : OPF Concept (Marchwinski et al., 2008)

It is observed that using one piece flow prevents fluctuations on cycle times and make the quality defects be detected early. It also affects positively built-in-quality concept. Because OPF concept clarifies one piece's quality defects instead of noticing the defect too late after the assembly is completed, which may be too difficult or costly to correct.

3.10 Forms and Supplemental Materials Used in the Game

Yamazumi Game uses several lean practical applications and industrial engineering approach. Thus, there is a big necessity of using effective forms and manuals to create an effective activity. Modified instructions manuals of LEGO to define the process phases, the rule cards that define the details of each phase, the data collecting forms to record the production outputs and evaluate the KPIs, and the problem solving forms to write down the problems encountered during the assembly process in each phase and create a discussion atmosphere to suggest solutions to these problems.

3.10.1 Instruction Manuals

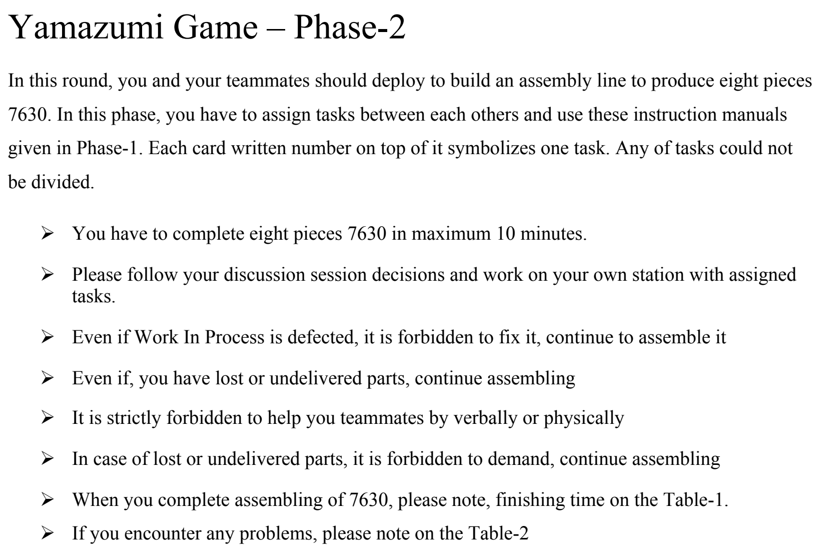
The original instructions manual of model 7630 that has much more details and visualizations is modified to define the process phases effectively. While some process phases are cancelled because they require gluing, other process phases are separated for an easier explanation. Each process cards are put in numerical order and holed to combine with a bead chain (see figure 3.16).

Figure 3.16 : Bead Chained Process Instructions Manual

There is a practical advantage of using a bead chain to combine cards. The bead chain can be easily removed to separate cards that are required by different stations. This way an operator at a given station keep only the cards he needs, not the entire set of cards. The use of bead chain can be considered as a kaizen, i.e. continuous improvement activity, since it makes the operator save time by eliminating the need to turn pages to find the specific activities among a big set of activities. The detailed instructions manual is provided in Appendix A.

3.10.2 Rule Cards

The most effective way of controlling groups and people is defining rules phase by phase for each session. Hence, in each phase of Yamazumi Game, the rule cards that define the responsibilities of each team member and the details of the production methodology are distributed. After distributing the rule cards, 5 minutes is given to the teams to read and understand the rules of each phase of the game. Detailed rule cards are given in Appendix B. See figure 3.17 for a sample rule card.



Yamazumi Game – Phase-2

In this round, you and your teammates should deploy to build an assembly line to produce eight pieces 7630. In this phase, you have to assign tasks between each others and use these instruction manuals given in Phase-1. Each card written number on top of it symbolizes one task. Any of tasks could not be divided.

- You have to complete eight pieces 7630 in maximum 10 minutes.
- Please follow your discussion session decisions and work on your own station with assigned tasks.
- Even if Work In Process is defected, it is forbidden to fix it, continue to assemble it
- Even if, you have lost or undelivered parts, continue assembling
- It is strictly forbidden to help you teammates by verbally or physically
- In case of lost or undelivered parts, it is forbidden to demand, continue assembling
- When you complete assembling of 7630, please note, finishing time on the Table-1.
- If you encounter any problems, please note on the Table-2

Figure 3.17 : Rule Card Sample (Phase 2)

3.10.3 Problem Solving Forms

PDCA methodology is used to understand and define problems by the participants. Specially designed PDCA forms based on Getting the Right Things Done book by Dennis (2006) help the participants think in a systematic way. This form is used for improving the results of output analysis (see Appendix C; Appendix D) and make discussions effective. PDCA forms (see Figure 3.18) are distributed to each team so that they write down the problems they encounter during the assembly and the countermeasures (i.e. preventing activities) for these problems to improve the system. (see appendix E)

	PLAN		DO	CHECK	ACT
Problem No	Problem Occured	Station No	Counter Measures	% Improvement	Standardization Comments
1					
2					
3					
4					
5					
6					
7					

Figure 3.18 : Problem Solving Form

3.10.4 Data Collecting Forms

At the end of each phase, the production outputs (such as completion times, defective products etc.) are recorded on a data form (see figure 3.19) in order to evaluate the performance of each phase. Measurement of Key Performance Indicators and evaluation - discussion period is needed to set new targets. Success of each phase is described by the KPIs. Total Lead Time, cycle time, number of quality defects are defined and filled on flipchart forms by the instructor. Calculations of the KPIs are defined in section 4 (see also appendix D).

Phase-3	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Output Times (sn)								
Line Cycle Time (sn) (Between Product)	0							
Defect Parts (Please Thick)								
Total Process Time based on 1st Product			**Lead Time**					

Figure 3.19 : Data Collecting Form Sample (Phase 3)

4. APPLICATION OF THE GAME AND EVALUATION OF RESULTS

Yamazumi Game is an experiential learning methodology on operations management (Ammar, 1999) that is designed to make people get experience by working on an assembly line. By playing the Yamazumi game, the participants learn lessons in an entertaining work atmosphere. Yamazumi Game has 3 phases, each of which is designed considering Kolb's four-phased learning theory (Dieleman and Huisingh, 2006).

This study evaluates the effectiveness of learning in two main sections described below. The comparison and evaluation period where the value of using lean concepts in assembly line design is numerically evaluated (see Appendix F) are presented in the following two sections named as *Participant Evaluation Period of the Yamazumi Game Outputs and KPIs* and *Results and Progress of Improvement Between Phases*

4.1 Participant Evaluation Period of the Yamazumi Game and KPIs

The aim of Yamazumi Game is to show the participants the effectiveness of lean methodologies and industrial engineering approaches in assembly line design. This requires the performance measurement of the two assembly lines designed by the participants, one considering the lean concepts and the other without lean concepts. Some key performance indicators (KPIs) are needed to see the improvement effect assured by lean methodology in the Yamazumi Game, which will persuade the participants about the success of the game. The KPIs are used only for comparing the results of Phase 2 and Phase 3 (see Appendix G). The results of Phase 1 are used to just evaluate the participants' individual performance.

4.1.1 Performance Evaluation of Participants in Phase 1

In Phase 1, the participant profiles are analysed based on age, sector and the completion times of the assembly of one unit of product (see Appendix H.1). The results are observed to see if there is any apparent relation between the completion times and age and sector of the participants.

First, we analysed the completion times without any sort of classification. We plotted the histogram of the completion times considering 130-second binned intervals. Average completion time of 80 participants is 1,035.52 seconds while, minimum completion time of one unit product is 490 seconds and maximum completion time is 1,653 seconds.

Bin (k) is calculated using the formula below:

$$k = \frac{\max x - \min x}{\sqrt{n}} \tag{4.1}$$

$$k = \frac{1653 - 490}{\sqrt{80}} = 130.6$$

Completion times are positively skewed and have a high standard deviation of 328.3 seconds (see Figure 4.1). The details about the completion times of the participants are reported in Appendix C.

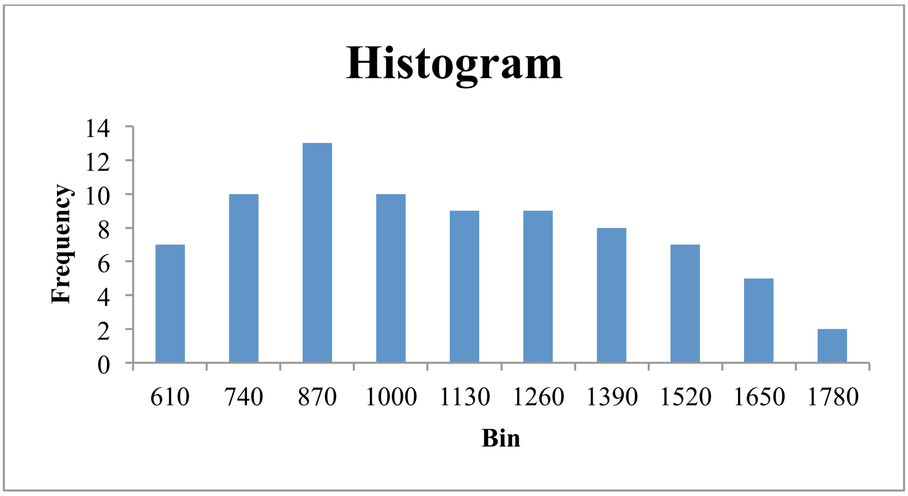


Figure 4.1 : Distrubution of Completion Times

4.1.1.1 Manufacturing Sector Based Evaluation

The manufacturing sectors can be grouped based on the production nature (King, 2009). Production flow is considered to define the different sectors. If the production flows one by one like the ones on assembly lines, this type of manufacturing is called discrete manufacturing. Discrete manufacturing businesses, also known as ‘A’ type processes, are focused on meeting the customer demands and wants. In discrete manufacturing sectors, the factories have to create a flexible production system varying on a based product. Assembly lines are the origin of flexibility in discrete manufacturing. See figure 4.2 for an example assembly process in a discrete industry.

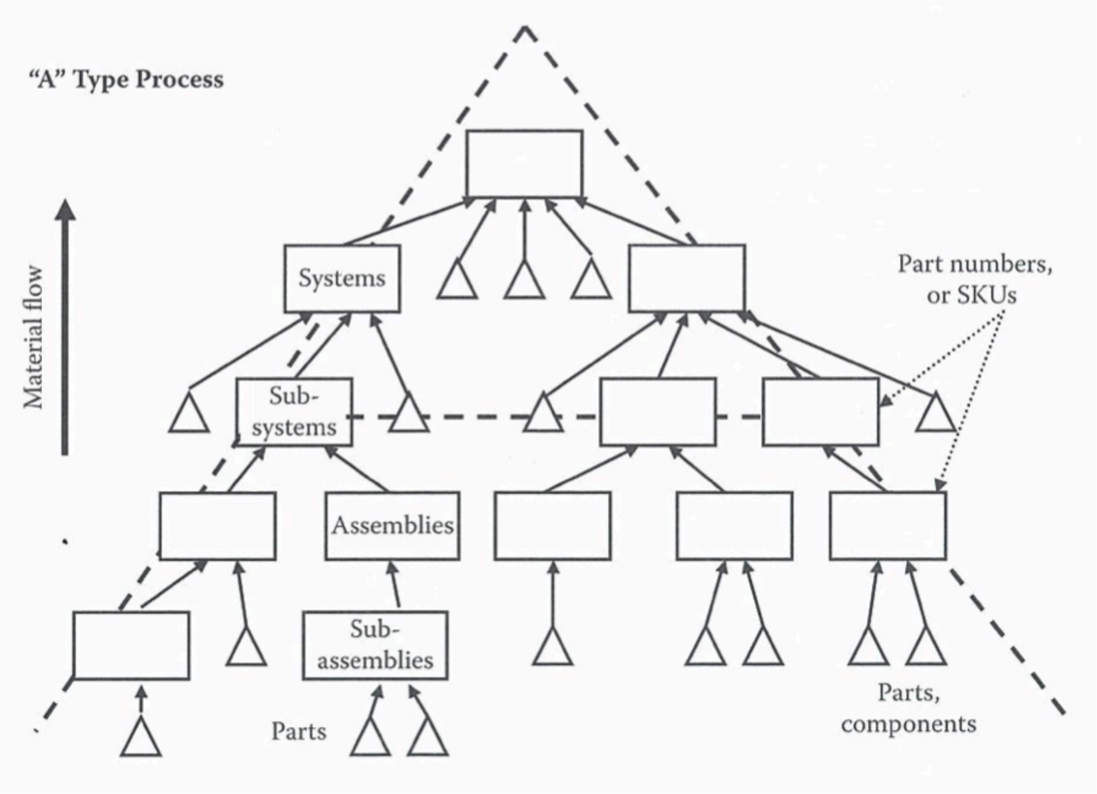


Figure 4.2 : A Type or Discrete Industries (King, 2009)

If the product is liquid, gas or other similar forms and if it is produced in continuous flow (extrusion, lamination, molding etc.) this type of production is continuous.

Continuous production can be defined as the production that makes physical or chemical change on a material while it is manufactured (Granger, 1989).

On the other hand, we can classify the production flows as door to door (from warehouse to shipping). If materials are getting diversified toward shipping i.e. the final product is diversified, this type of production is called as V type industry (see figure 4.3); otherwise it is called as discrete industry or A type industry where the products are getting similar while going toward the finish processes (King, 2009).

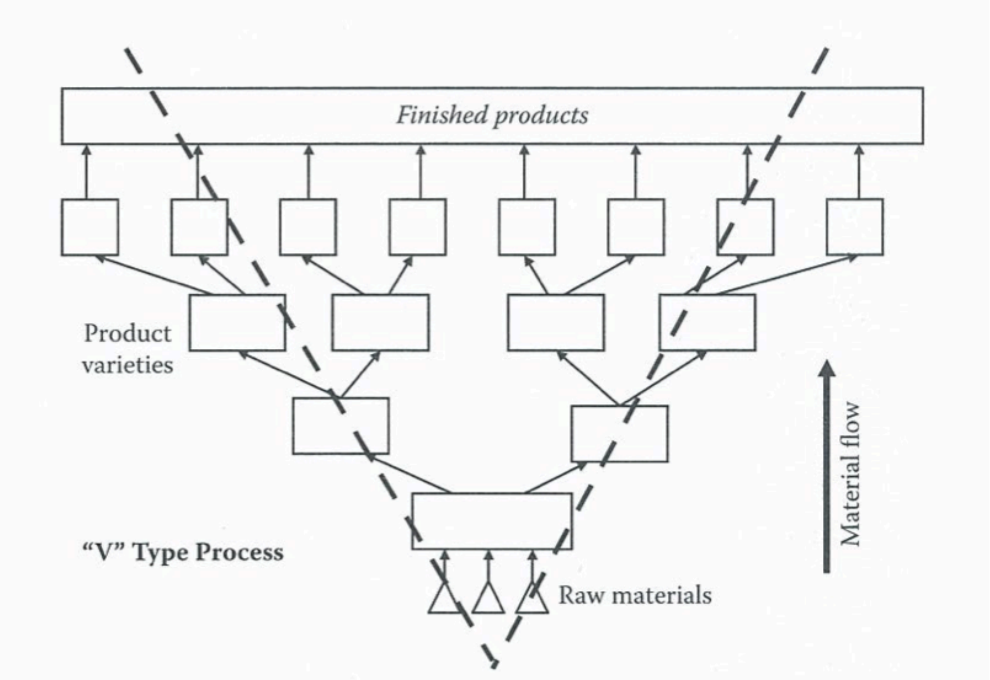


Figure 4.3 : V Type Process Industries (King, 2009)

Participants of the Yamazumi Game come from either discrete or continuous production industries. 20% of the participants are from process industries (food packaging, window profile manufacturing, molding, food industries) and 80% of them come from the assembly plant nature (automotive manufacturing, automotive suppliers, white goods, furniture, textile) (See Appendix C).

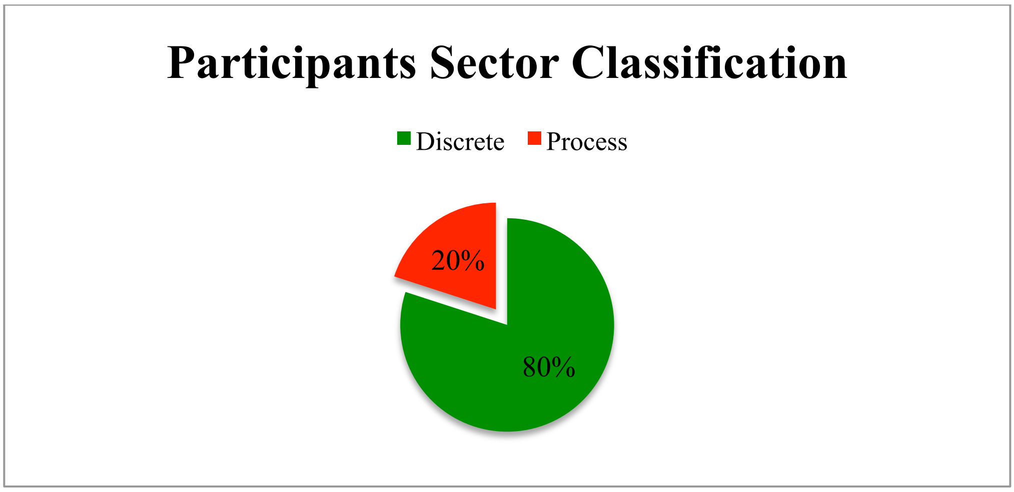


Figure 4.4 : Sector Based Classification of Participants

When we analyse the average completion times for the different sectors, which are reported in Figure 4.4 and Figure 4.5, we observe that the completion times have a lower average for the participants coming from discrete industries.Because the number of participants from discrete industries is significantly higher than the number of participants from the other type of sector, the average completion time for discrete industries are closer to the general average while the process industries' completions times have a high deviation from the general average.

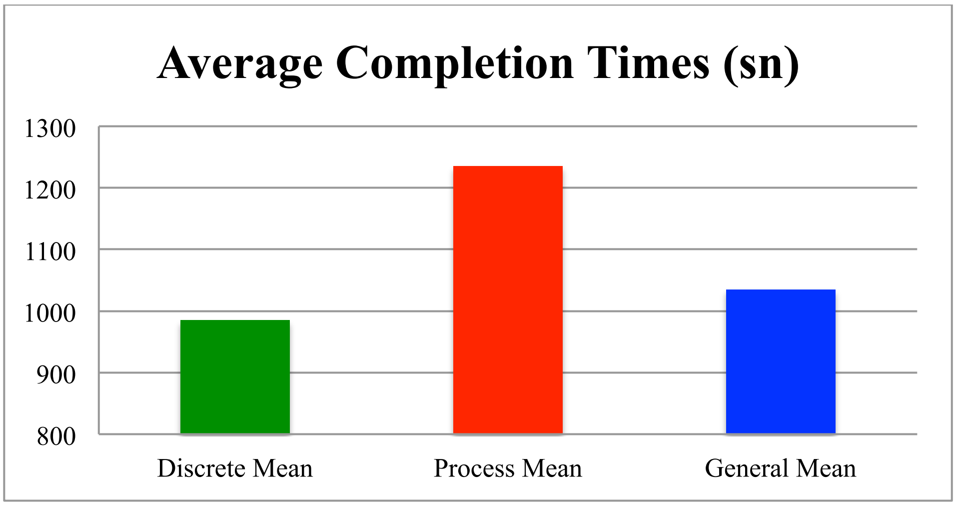


Figure 4.5 : Mean Completion Times for Sectors

4.1.1.2 Division Based Evaluation

This study also classifies the participants based on their divisions. Participants are classified into two groups as blue collar and white collar. 24% of the participants are blue collar and 76% of the participants are white collar working as either production engineer or executive as shown in Figure 4.6 and Figure 4.7. We analyse the completion times for this classification. The mean completion time for blue collars is 1001 seconds while that of white collars' is 1045 seconds.

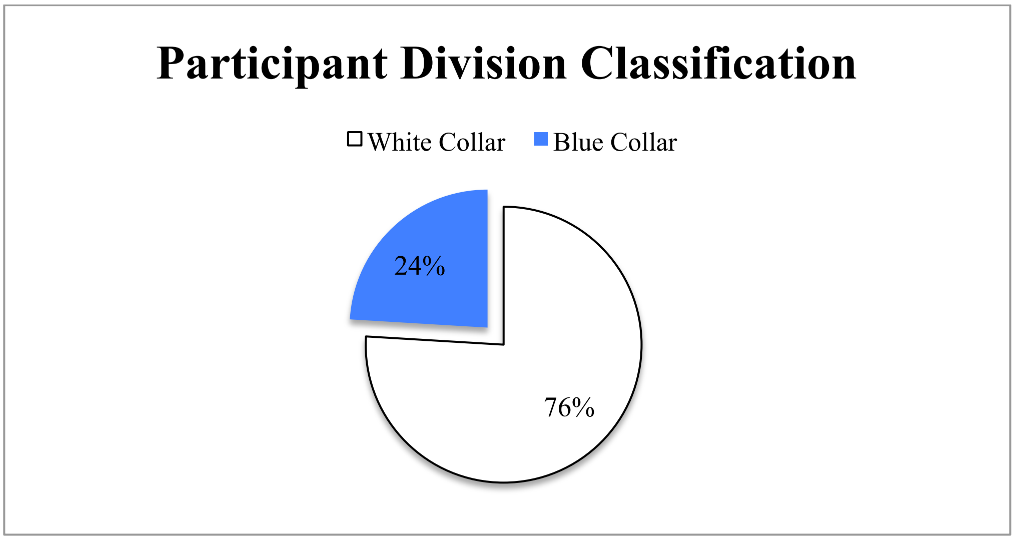


Figure 4.6 : Blue Collar- White Collar division of the participants

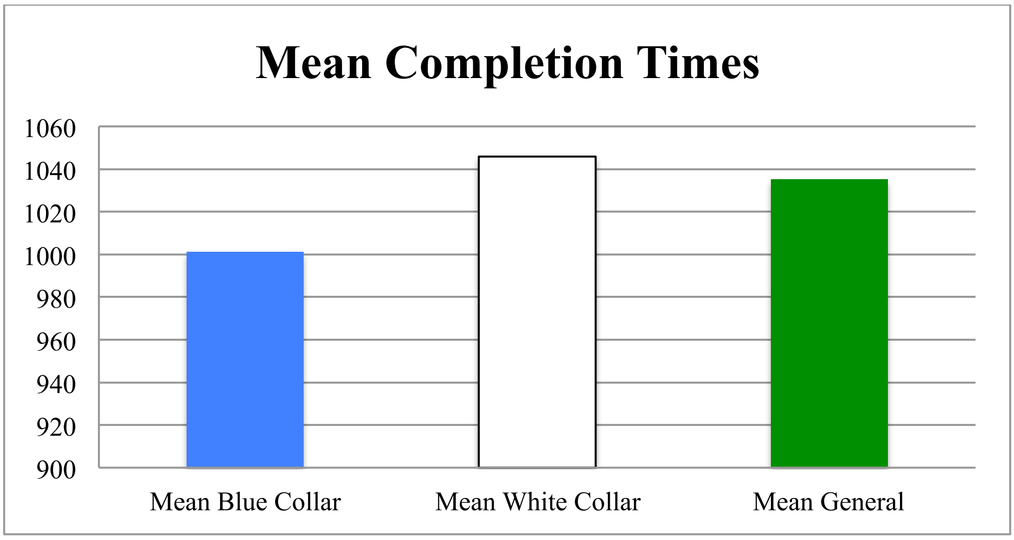


Figure 4.7 : Mean Completion Times of Blue and White Collars

This tiny gap between mean general and mean white collar is also observed in the workshops with the participation of a mixed group of people who are in different collars. Generally blue-collar participants are more energetic and active working on the assembly lines and they are more suitable to improve and drive the teams.

4.1.1.3 Age Based Evaluation

The relation between the completion times and the age of the participants of Yamazumi Game is also analysed. The minimum and maximum ages among the participants were 26 and 56, and the participants are classified into 5-year binned age groups. The ages of 34% of the participants are between 26-30 years. Figure 4.8 shows the percentages of the participants in all the age groups, which ranges from age group 26-30 to 56-60.

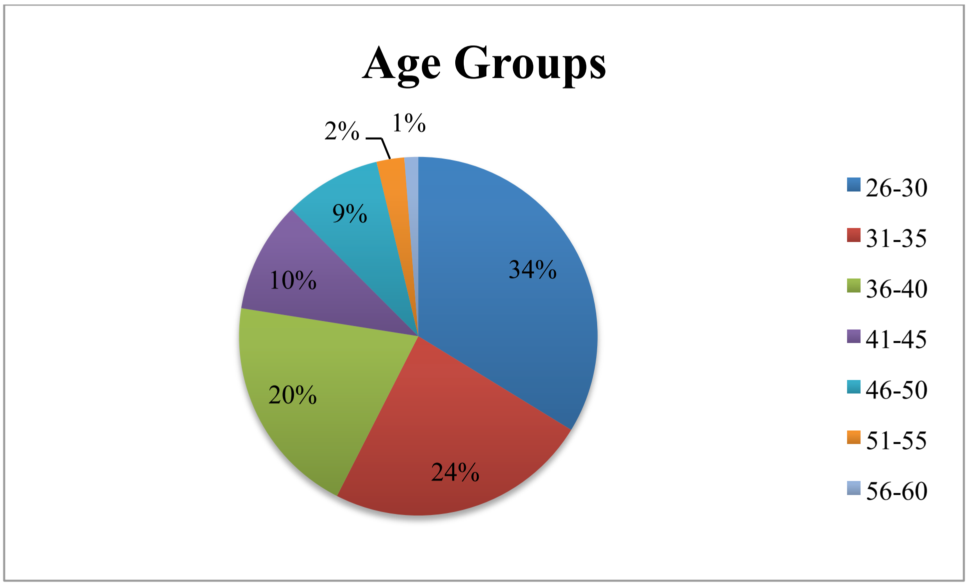


Figure 4.8 : Age Groups of Participants

In workshops, we have observed that some elder participants can not complete the assembling of the product in Phase 1 where they are asked to individually do the complete assembly of one unit of product. This raised the question: “Is there a relation between age and completion time?”

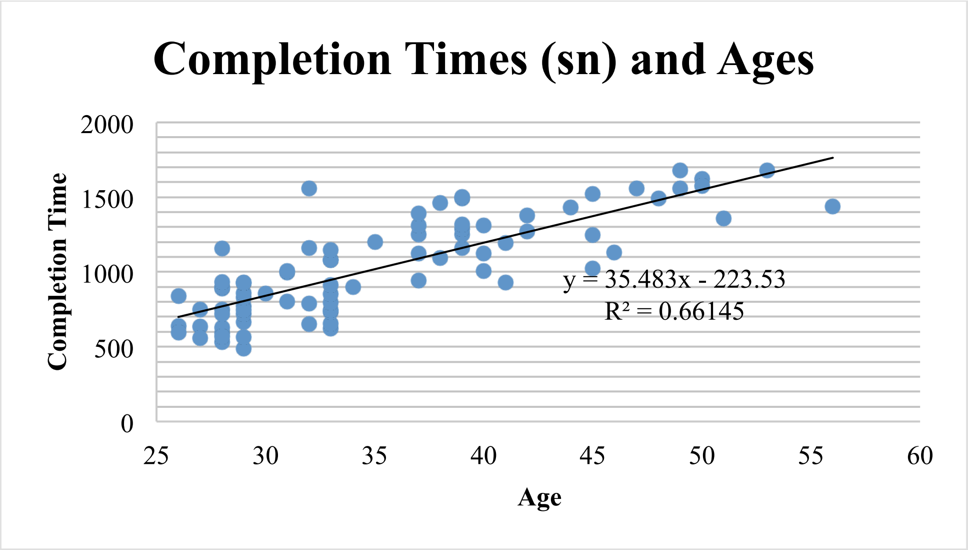


Figure 4.9 : Completion Times and Ages of Participants

Figure 4.9 plots the completion times with respect to the age of the participants. It is apparent from the plot that there is a relation between age and completion times and as the age increases, the completion time increases. A linear regression is run over 80 data points and the results in Table 4.1 are obtained.

Table 4.1 : Table Regression Statistics of Plotter Diagram

Regression Statistics	
Multiple R	0,813295462
R Square	0,661449509
Adjusted R Square	0,657109118
Standard Error	4,406664487
Observations	80

The linear function that results from linear regression is: Completion time = 35.5*age-223.5. Hence, the completion time is expected to increase by 35.5 seconds as the participants gets one year older. R^2 value of this regression line means at least %66,1 of the change in completion time can be explained by age. R^2 value is also calculated manually and details of this calculation can be found in Appendix H.2.

4.1.2 Game Outputs and KPIs in Phase 2 and Phase 3

There are three game outputs and three KPIs used for evaluating the performance. The three game outputs are cycle time, completion time of the production lot (lead time) and number of defective products. The KPIs calculated from game outputs (see figure 4.10) include coefficient of variation of cycle times, slope of regression line of measured completion times (considered as estimated cycle time), and labor time spent per quality product (*QPT*).

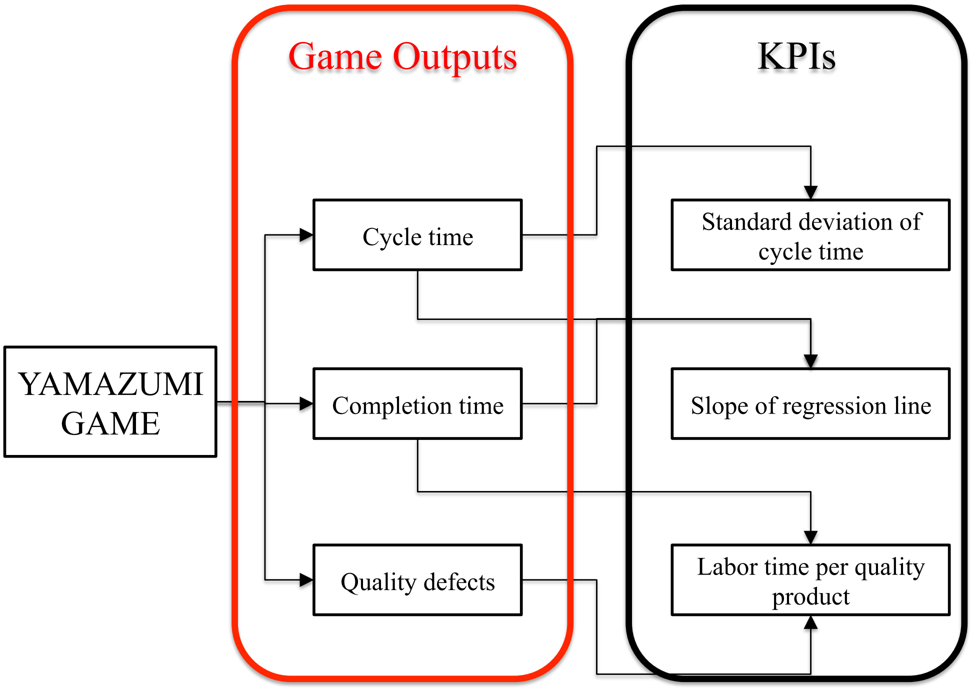


Figure 4.10 : Relation between Game Outputs and KPIs

4.1.2.1 Game Outputs Used for Workshop

Game outputs are used for performance evaluation of the teams between phase 2 and phase 3. Game outputs considered in this game (i.e. completion (output) time, quality defects and cycle time) are used practically in industries.

Completion Time (or output time - OT_i) : According to the lean methodology, 'value' has to reach the customer as soon as possible, thus from warehouse to shipping, the producer has to create value and flow it quickly to speed up cash flow and turnover

(Womack and Jones, 1996). For this reason, completion time is a critical performance indicator of Yamazumi Game. This data will be used to calculate performance rate.

The other lead time is called as order lead time which is the time between when the order is placed and when it is delivered (Marchwinski et al., 2008). In Yamazumi Game, the start of production is considered as the time at which the order is placed and the time at which the last product is out is considered as the time of delivery.

Quality Defects: Another lean performance measurement tool is the detection of quality defects and reworks. The producer should create a true value that the customer wants at the first time (Liker, 2004). Hence, in the Yamazumi game, the number of defective products produced by the participants that do not compile with the instructions for the Lego model 7630 is measured as a quality indicator. This is used for understanding the effectiveness of built in quality. In Phase 1 and Phase 2, finished products are tested for quality. Each finished product is controlled whether it has a missing or incorrectly assembled parts. In phase 3 each product is controlled in source i.e. at its own station. It is called as built-in-quality.

Cycle Time (CT): The third output of Yamazumi Game is used for understanding the non-stabilized product cycles. Cycle time is described as “How often a part or product actually is completed by a process, as timed by observation” (Marchwinski et al., 2008).

This output shows the participants the effectiveness of using standard work, stableness of the production rate when lean concepts are considered and the power of pull systems. Therefore, cycle time measurements are important for Yamazumi Game.

4.1.2.2 Key Performance Indicators (KPIs)

KPIs are used not only for performance evaluation but also understanding of the effectiveness of Yamazumi Game and Lean Concepts. Not only game outputs but also KPIs are used to clear suspects about performance improvements. KPIs are created for evaluating the performance difference between phases 2 and 3. These KPIs are estimated cycle time (slope of regression line of completion times), coefficient of variation of cycle time and labor time spent per quality product (*QPT*).

Coefficient of Variation of Cycle Times: The coefficient of variation of cycle times indicates the stability of the performance of the line. For instance, while completion time values are smaller for some teams, cycle times may have significant deviations. That is why when evaluating the performance of the lines, the standard deviation of cycle times also should be taken into account along with the mean cycle times.

Estimated Cycle Time: Completion times of products are measured in both Phase 1 and Phase 2. Linear regression is run over completion times. The slope of the regression line shows the estimated time to produce an additional unit of product, i.e. estimated cycle time for the assembly line. The estimated cycle time based on linear regression is denoted as CT_{LR}.

Labor Time Spent per Quality Product (QPT): The third KPI considered is labor time per quality product. It is calculated as the total man-hour spent divided by the number of non-defective products produced. Lean methodology aims to eliminate wastes (Womack and Jones, 1996). Hence, the participants try to avoid all seven wastes (unnecessary transportation, inventory, motion, waiting, over-processing, over-production and defects) in their simulated assembly lines in Phase 3, so the rate of man*hour per quality product is expected to decrease from Phase 2 to Phase 3.

4.2 Results and Progress of Improvement Between Phases

Yamazumi Game is as an experiential learning tool, which is created by Can Yukselen. This training program has been offered to several organizations by Lean Institute Turkey for two years. The participants of the Yamazumi Game come from different industries, divisions (blue collar/white collar) and age groups. Yamazumi Game is offered to not only to participants working in manufacturing areas but also to the university students and professors.

The different backgrounds and profile among the participants provide interesting data regarding their adaptation period, the change management and teamwork. Results show that the adaptation behaviour of the participants show variability with respect to their divisions, ages and manufacturing experiences.

In this study, we consider the data collected from twelve workshops (i.e. 12 applications of Yamazumi Game) that are performed as either public trainings, company in-house trainings or in university student fairs. Each workshop had around 18-24 attendees aged between 20 to 56 years. Most participants are working as manager, engineer, team leader or worker in automotive, textile, food, sheet metal, furniture, moulding industries, or they are college students.

The aim of this workshop is to show participants the effectiveness of lean methodologies and industrial engineering approaches. Although the participants of the game differ with respect to work experience or age, it can be stated that each of them make an improved progress from one phase to the other in the game. Nevertheless, the progress level of each workgroup is different.

This study uses actual data coming from the workshops performed in order to numerically evaluate the improvement obtained by using lean methodologies in assembly lines.

Game outputs and key performance indicators are used to evaluate the performance improvement between Phase 2 and Phase 3 of the game. Statistical tests and linear regression are used to see whether the samples coming from different phases of the game are significantly different.

Several graphs are plotted to visually observe the changes in data between Phase 2 and Phase 3.

Graphs compares the regression lines that show the completion times of 1st, 2nd,…,last product produced by the assembly lines in Phase 2 and Phase 3. The slopes of these regression lines can be interpreted as an estimate for cycle time based on actual cycle times, and these slopes are compared to see if there is any improvement made by using lean methodology in Phase 3. In addition to this comparison, a statistical test, namely paired t tests are performed to see if there is any significant change in performance between phase 2 and phase 3.

Furthermore, paired t tests are also performed to see if there is any improvement in the number of defective parts, the coefficient of variation of cycle times and the QPT. The following sections include a detailed numerical analysis that are performed to prove the improvement effect of using lean concepts.

4.2.1 Comparison of Phase 1 to Phase 2

In this study, we do not compare the performance of the participants between Phase 1 and Phase 2. Because, Phase 1 is just a warm-up session where the participants are introduced how to assemble a LEGO product. In this session, they are provided the LEGO® parts of the product chosen and the instructions manual for its assembly. In Phases 2 and 3, the participants are grouped into teams to work on assembly lines they design considering the information provided to them in each phase. Each person works in a single workstation and do a group of assembly tasks assigned to this workstation. Hence, each unit of product is produced using teamwork. In this study, we compare the performances of the assembly lines formed in phases 2 and 3.

Workload sharing, i.e. each person being responsible of a group of tasks needed for the assembly of a product, is known to result in lead time reduction. Workload sharing has been successfully applied in many industries since 1911 (Taylor, 1911). Yamazumi Game let the participants experience the beneficial effect of workload sharing in the assembly of a product. While in Phase 1 of the game the participants work individually on assembling an entire product, in phases 2 and 3 they form an assembly line where they share the assembly workload.

4.2.2 Comparison of Phase 2 to Phase 3

In phases 2 and 3, the assembly lines where the workstations share the workload are used. Nevertheless, the main idea of Yamazumi Game is to show the participants the effectiveness of using lean methodology and tools on assembly lines. Phase 3 of the game is an upgraded version of Phase 2 that is improved by lean tools and trained participants who performs on line.

This study uses game outputs (completion time (output time), quality defects, cycle time) and KPIs (coefficient of variation of cycle times, slope of regression line of completion times, labor time per quality product) to evaluate the performance between Phase 2 and Phase 3. First, the actual performance of the assembly lines in each phase is measured using these game outputs and KPIs. Then, the KPIs for the two phases are compared to each other using paired t-tests to see if there is any significant difference between the performances of these phases. For comparison purpose, the actual performance of 12 teams are used in the numerical study. Finally, according to the paired t-test results, some evaluations and discussions are made regarding the effectiveness of lean methodology.

In this section, some representative results regarding the game outputs and KPIs are provided while all evaluations can be found in Appendix F. For example, Table 4.2 reports the values of game outputs that are used to evaluate the performance of Team 2 in Phase 2. A similar table is made for the performance of each of 12 teams in both phases 2 and 3. First and third metric reported in Table 4.2, completion times for final products that exit the assembly line and the number of defective parts are actual values measured during the workshop. The second metric is calculated using actual completion times, as explained below.

Table 4.2 : Game Output table for Team 2 in Phase 2

Metrics	**Product *i***							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Act. Completion or Output Time (OT_i) (in seconds)	631	750	802	848	901	952	993	1041
Line Cycle Time (CT_i) (in seconds)	-	119	52	46	53	51	41	48
Defective Product (DP_i)	0	0	0	1	1	1	1	1

The cycle time is defined as the inter completion time, i.e. the difference between the completion times of any two consecutive products, which is calculated as:

$$CT_i = OT_i - OT_{i-1} \text{ for } i = 2,3\ldots,8 \tag{4.2}$$

where OT_i represents the output (completion) time of ith product coming out of the assembly line and CT_i represents the ith CT calculated for the assembly line. For example, 4th cycle time reported in Table 4.1 represents the intercompletion time between 4th and 5th products (901-848=53). CT_1 is not defined since product 0 does not exist.

The third metric reported in Table 4.2, DP_i, represents whether or not the i^{th} product conform to the instructions manual. If the product has at least one defect, this metric takes the value of 1 if it is non-defective then it takes the value of 0. Clearly, $\sum_i DP_i$ shows the total number of defective products produced by the assembly line. It is expected that the participants decrease the number of defective products without having to cease the production.

Table 4.3 : General Information Table for Team 2 in Phase 2

Key data for performance rate calculation for team 1	***Phase 2***	***Phase 3***
Number of workers	5	5
Number of products per produced	8	8
Number of defective products	5	3

In addition to the data provided in Table 4.2, other critical information is also provided, such as the number of team members and the team leaders used in the assembly line, the total number of defective products and the coefficient of variation (CV) of cycle times (see Table 4.3). The coefficient of variation of cycle times is an important indicator to show the stability of the performance of the assembly line. For example, team 2 has five team members without team leader and produces 3 of 8 quality products. CV of their assembly line is 26.96. For detailed information about number of team leaders, team members, standard deviation of cycle time and quality products, see Appendix G.

In addition to the information provided in table 4.2, we also plotted some key data to show the performance of the teams visually. Below we provide some representative graphs for a team's performance in phases 2 and 3 while the graphs for all teams can be found in Appendix G

Two graphs are plotted in order to evaluate the performance of individual phases and also compare the performances of the two phases.

First graph (see Figure 4.10) is plotted by using the actual completion times reported in Table 4.2 for the products 1 through 8 produced by Team 2 in phase 2. This figure is important because it shows not only learning effect of team or adaptation but also gives information about performance fluctuation. The fluctuation on output times in Phase 3 is expected to be lower than that of Phase 2. Because, the use of a team leader and other lean tools in the assembly line should have an effect of increasing the stabilization of the performance of the team members. This can be seen by comparing Figures 4.11 and 4.12.

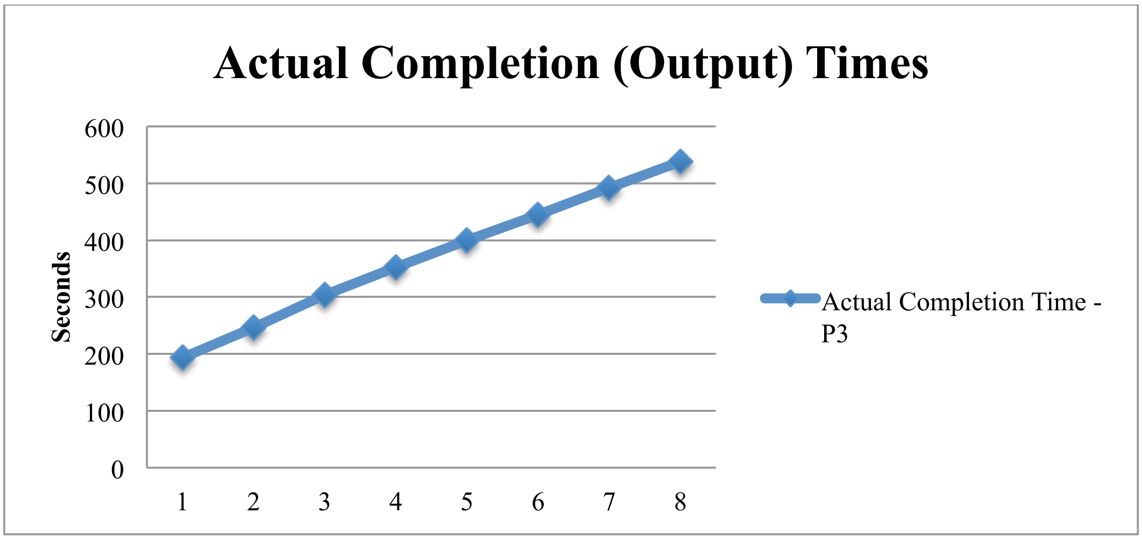


Figure 4.11 : Actual Completion Times by Team 2 in Phase 2

Figure 4.13 is plotted for performance comparison of Phase 2 and Phase 3. The linear regression is run over the actual completion times in Phase 2 and Phase 3. The slope of regression lines represents the estimated cycle time. The estimated cycle times in different phases are compared to see if there is any improvement in cycle times provided by the use of lean tools in Phase 3. The gap between the actual completion times in Phase 2 and Phase 3 can also be clearly seen from Figure 4.13.

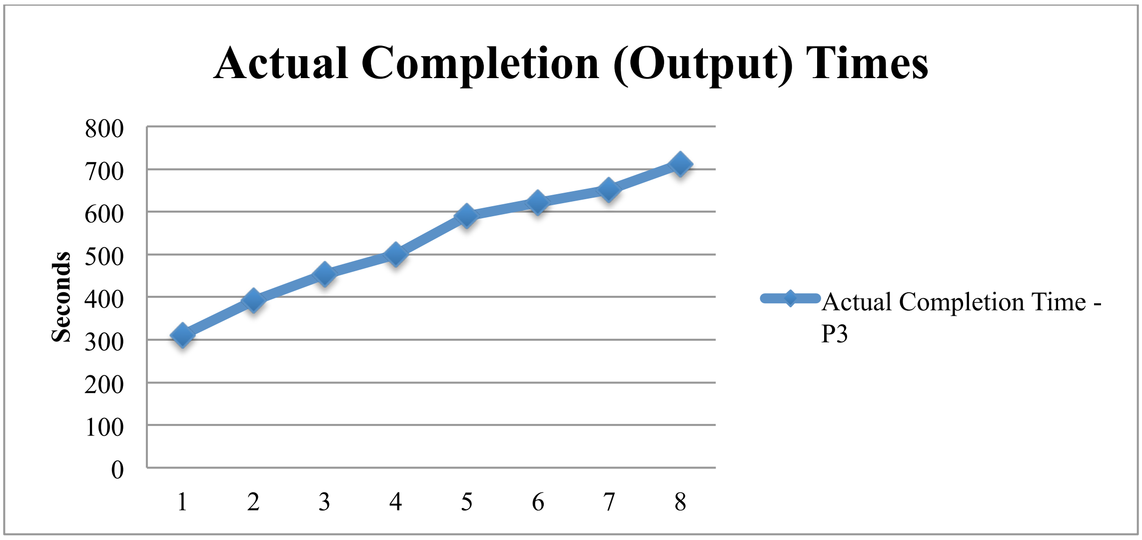


Figure 4.12 : Actual Completion Times by Team 2 in Phase 3

If there is no significant gap between the lines that passes through the actual times in Phases 2 and 3, that means no performance improvement is obtained from Phase 2 to Phase 3. A similar interpretation can be done also by comparing the slopes of the regression lines.

Slope of Phase 2 line is expected to be higher than the slope of Phase 3 line. According to Figure 4.13, there is a slight improvement in cycle times in phase 3 compared to phase 2 (56.4 s versus 49 s) while there is significant improvement in the completion times of the first product (193s versus 365s) in phase 3.

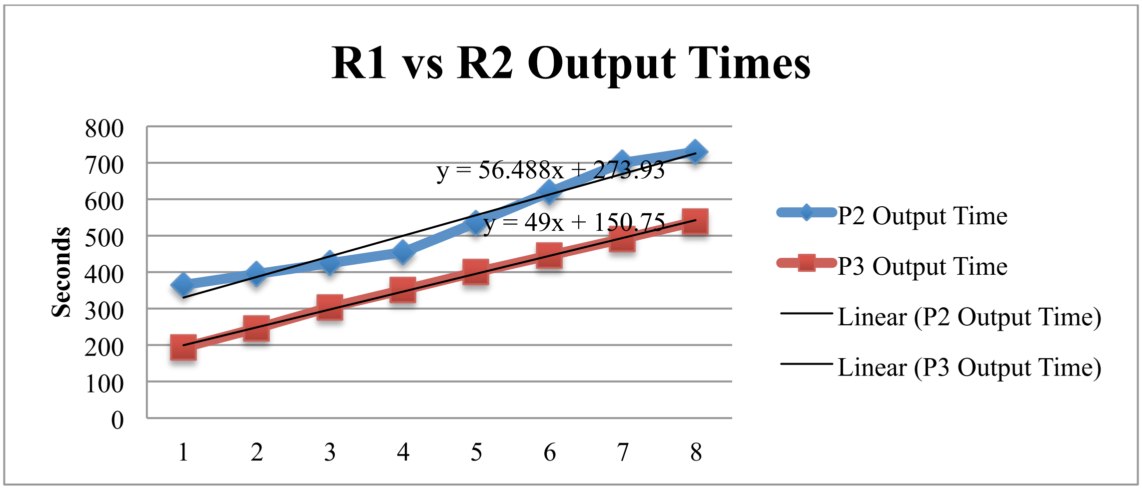


Figure 4.13 : Actual Completion Times and Estimated Output Times by Linear Regression in Phases 2 and 3 by Team 1

4.2.2.1 Effect of Lean Methodology on Assembly Line based on KPIs

A main advantage of lean assembly lines is to clarify problems that is the opportunities for continuous improvement (Liker, 2011). This results in stability of flow and decreases quality defects. In Phase 3, the participants who are introduced the lean concepts are given the chance to redesign the assembly line. The instructor observes the performance of the participants on the new assembly line by measuring the game outputs and KPIs.

The actual completion times increases at a decreasing rate as the number of products produced increases as can be seen in Figure 4.14, which plots the completion times of the products produced by a team in Phase 2. The decreasing rate, i.e. the decreasing cycle time, can be explained by the learning effect. As the participants perform the tasks repeatedly, they learn better and they do the same tasks faster. Phase 2 output times are proof for adaptation of people but unfortunately far from stabilization.

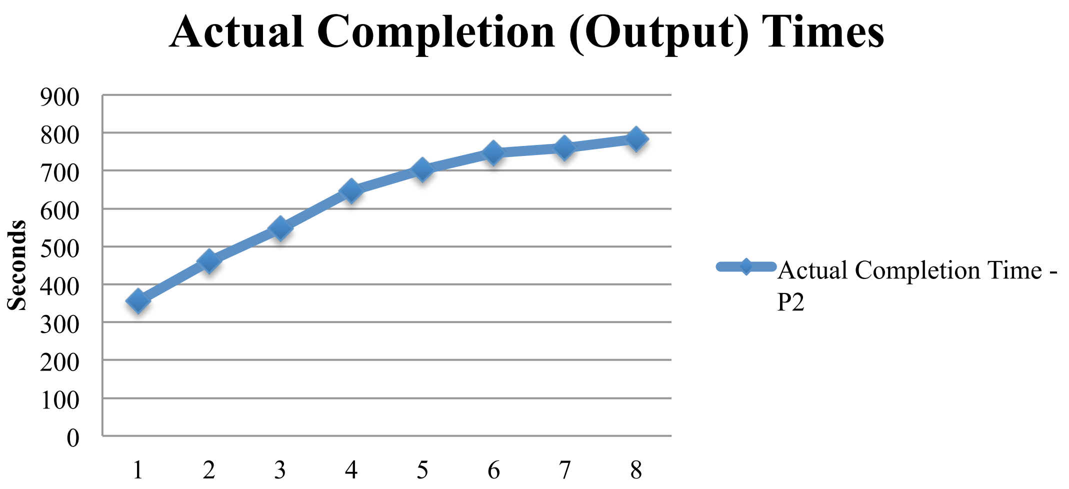


Figure 4.14 : Actual Completion Times by Team 6 in Phase 2

On the other hand, Figure 4.15 which plots the completion times by another team (team 5) shows a different behaviour than the one shown in Figure 4.14. The actual completion times of Team 5 in Phase 2 performs upward trend till producing fourth product. After this, it shows gradual increase until completing all products and differentiates from estimates.

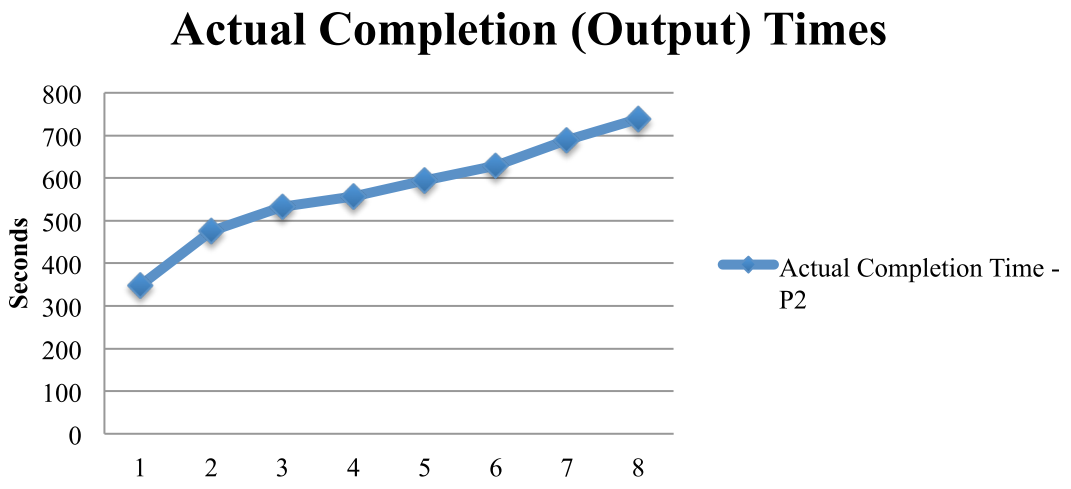


Figure 4.15 : Actual Completion Times by Team 5 in Phase 2

This result shows us there are another effects on variability because of inventory fluctuations and layout of line. That is why we can not say there is a clear learning effect in Phase 2. It could be many reasons effecting completion times and fluctuate cycle time levels.

One of the important effect of fluctuation on Phase 2 is line layout. If teams design a parallel located stations (see Figure 4.16) and has no well assigned jobs, products flow quickly until reaching the last operation. The last operation of line detects total performance of team; even previous stations have produce so much efficient.

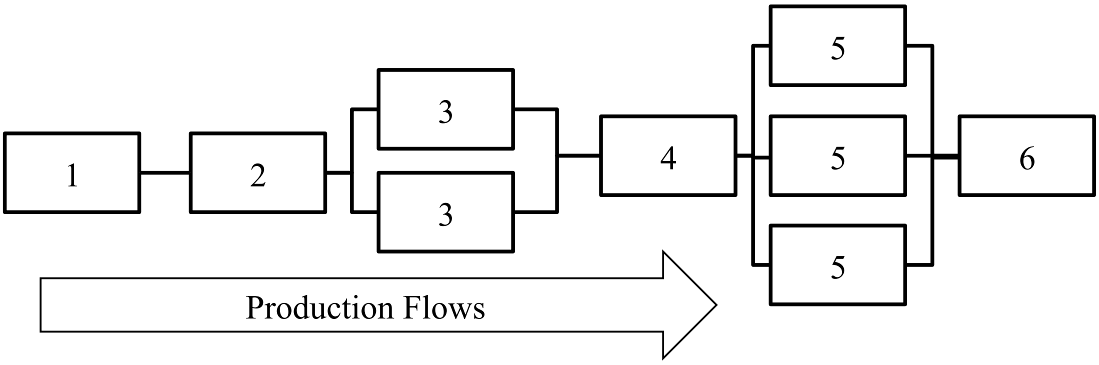


Figure 4.16 : Parallel Located Stations

Inventory accumulation on the line effects cycle times. It is observed that; many of teams assign less jobs to first stations and this causes producing WIP (work in process). WIPs flow quickly through the last station when production starts. These WIP has to be assembled by the final workstation. This line organization does not change total process time of first product; but performance of the line is not as good as expected even if the last station performs well. Because big percentage of workload accumulates on the last station.

Nevertheless, production does not continue as it is gone for the first product. Because, unbalanced assigned jobs and increasing inventory levels create illusory efficiency. After first product out, performance of the line is as speedy as the last station. Normally, other team members could help the last station after they finish their tasks in this game, but it is against the rules defined for this game (see Appendix B). This rule of the game conforms with real life production that has to continue during the day where the line must not to be stopped, and so the team members are not able to help the last station.

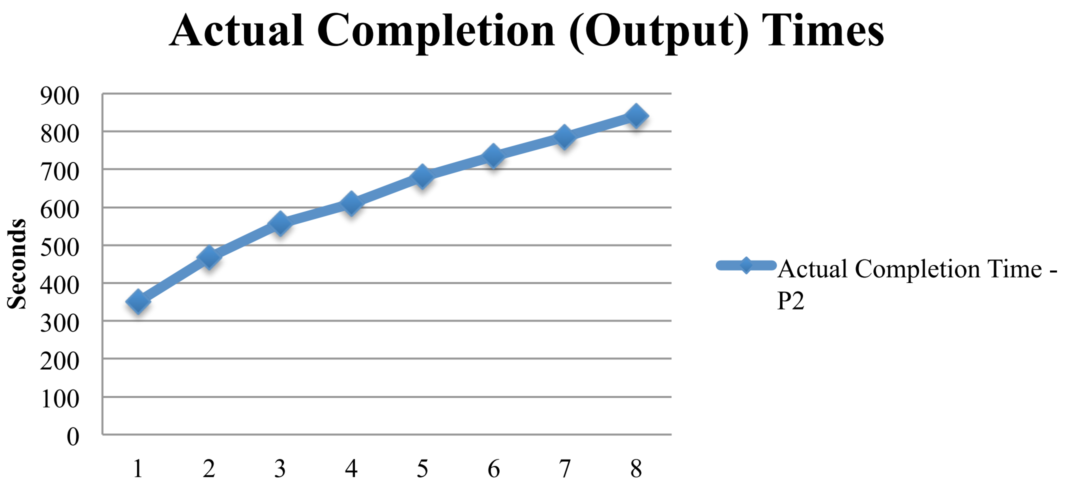


Figure 4.17 : Actual Completion Times by Team 8 in Phase 2

Another important cause for fluctuation on graphs is the required rework for defective parts. It is observed that when the numbers of defective parts are numerous, which requires the workers to spend time for rework to fix the problem, this results in non-steady completion times, i.e. the completion times do not linearly increase as the number of products increases. This is shown in Figures 4.17-4.20, which plots the completion times obtained by Team 8, Team 3, Team 11 and Team 12, respectively.

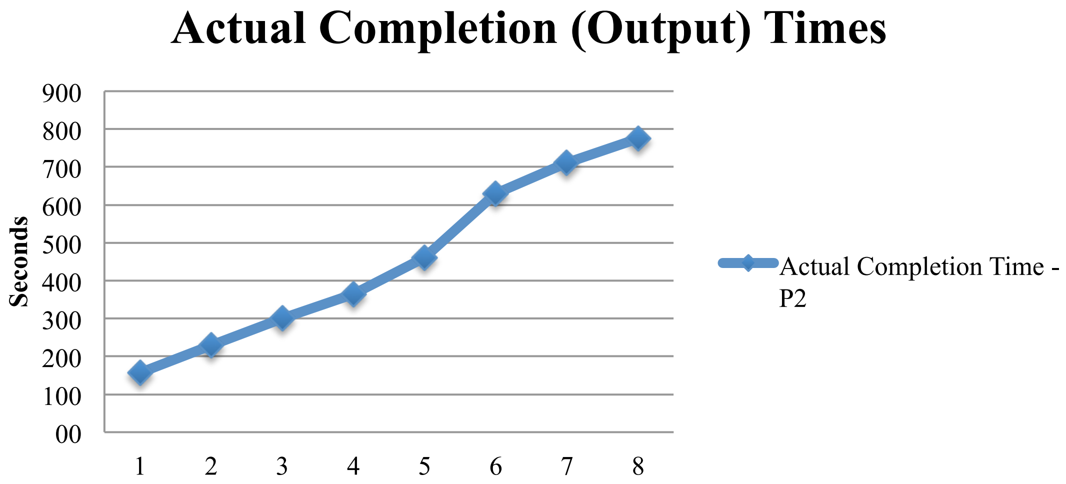


Figure 4.18 : Actual Completion Times by Team 3 in Phase 2

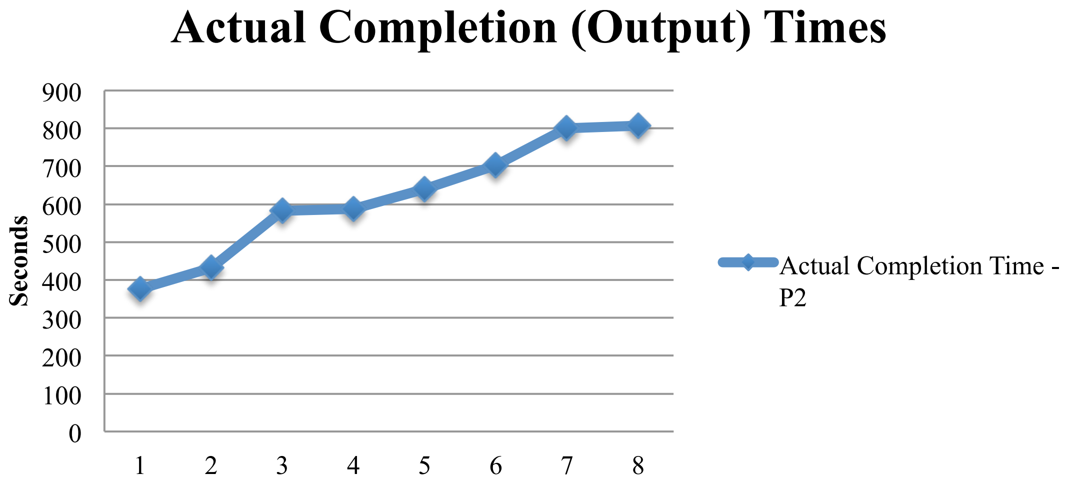


Figure 4.19 : Actual Completion Times by Team 11 in Phase 2

These evaluations done for Phase 2 are also done for Phase 3. In general, we can say that the stabilization of performance has dramatically changed in this phase. Deviations and fluctuations of actual cycle times are also reduced. However, we have observed extraordinary results as well such as having better actual times in Phase 2 compared to those in phase 3 (See figure 4.21).

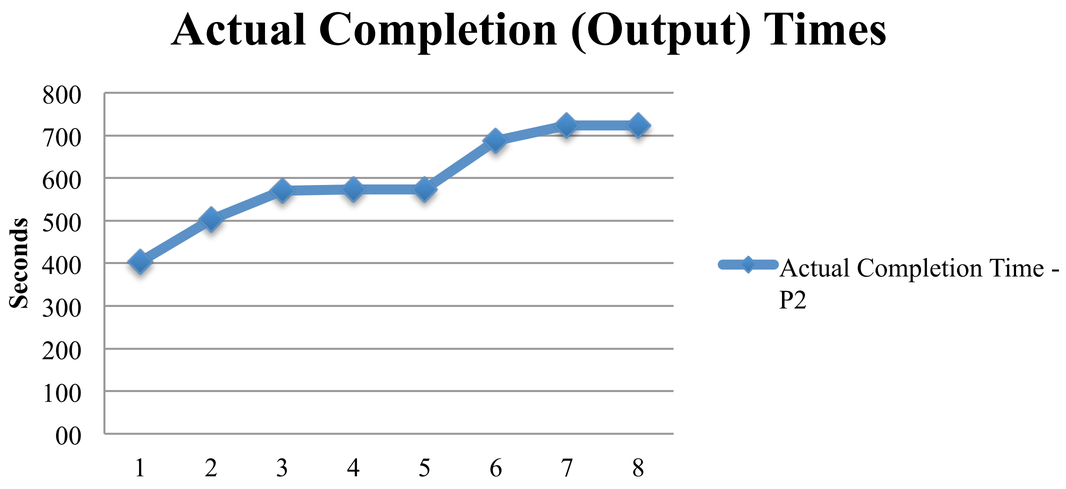


Figure 4.20 : Actual Completion Times by Team 12 in Phase 2

Fluctuation of actual completion times have dramatically decreased in Phase 3 compared to Phase 2 as can be seen from Figure 4.21 for Team 3. Stabilization is provided by one people chosen from this team as a team leader who helps the other members in case they need help.

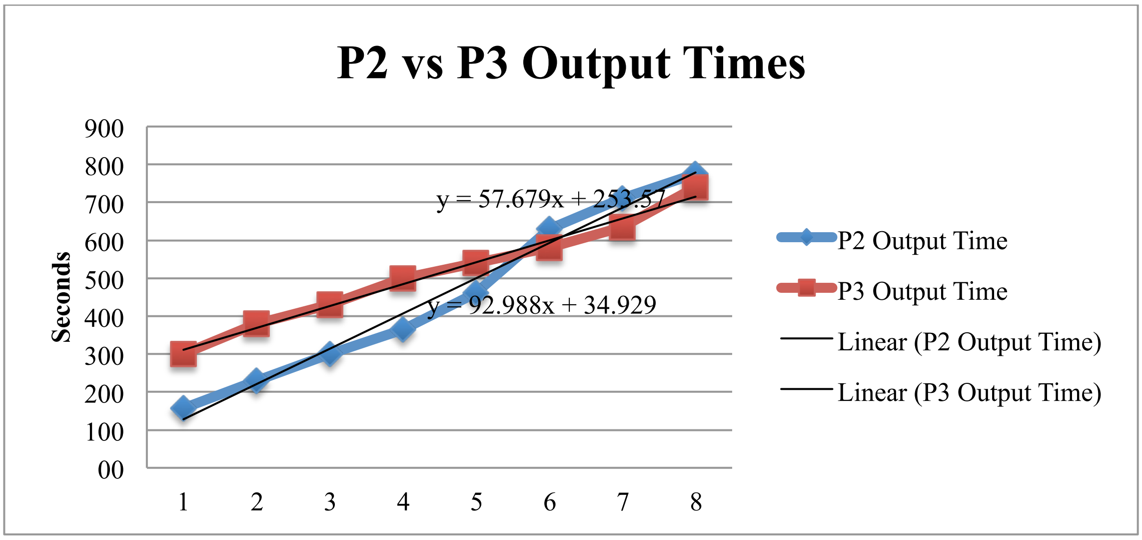


Figure 4.21 : Comparison of Team 3 Performance in P2 and P3

Decrease of fluctuations in cycle times that can be visually observed in the graphs is also verified by calculating the coefficient of variation of cycle times. Low coefficient of variation, gives information about the stability of product flow. If the coefficient of variation of cycle times is very high, it means that there are either non-controlled work in processes or defective products requiring rework.

In Phase 3, **One Piece Flow** and **Team Leader** concept as well as balancing the task times on Yamazumi board based on **Takt Time** (which is the maximum workload limit for each station), reduced the fluctuation in cycle times. Moreover, the designed **Poka Yoke** systems and **Standardized Work** instructions and **visual devices** implemented by the team members have also improved the stabilization of the system.

Coefficient of variation (CV) of cycle times is calculated for 12 teams in both phases 2 and 3, which are reported in Table 4.4. It is observed that the coefficient of variation decreased significantly in phase 3.

Table 4.4 : Coefficient of Variations (CV) of CT for 12 Teams in Phases 2 and 3

Team i	*Phase 2 CV*	*Phase 3 CV*	*Difference (d_i)*
1	0.531	0.094	0.437
2	0.460	0.401	0.060
3	0.425	0.378	0.047
4	0.414	0.086	0.327
5	0.612	0.052	0.560
6	0.603	0.101	0.502
7	0.303	0.118	0.184
8	0.351	0.105	0.246
9	0.130	0.087	0.043
10	0.150	0.047	0.103
11	0.835	0.283	0.552
12	1.066	0.415	0.652
		$\sum_{i=1}^{12} d_i$	3.711
		s_d	0.225

As can be seen from table 4.4, the coefficient of variation of cycle times for all teams in Phase 3 are lower than those in Phase 2. Further, we used paired t test to statistically show that the use of lean tools in phase 3 reduces the coefficient of variation (i.e. variability) of cycle time. Hence, we test this hypothesis to prove performance improvement effect of Yamazumi Game using Lean Methodology. We have applied

Paired t-test (two samples with unequal variances) to compare the data of coefficient of variations. The following hypothesis is tested.

$\mathrm{H_0}: \mu_\mathrm{d} = 0$

$\mathrm{H_1}: \mu_\mathrm{d} > 0$

Where μ_d represents mean population difference, $\mathrm{s}_{\bar{\mathrm{d}}}$ represents standard deviation of differences of 12 teams.

The test statistic for $\mathrm{H_o}$ is a t-statistic calculated as:

$$\mathrm{t} = \frac{\bar{\mathrm{d}}}{\mathrm{s}_{\bar{\mathrm{d}}}} \tag{4.3}$$

Where $\mathrm{d_i}$ represents the difference between phase 2 and phase 3 of team i, $\bar{\mathrm{d}}$ represents the mean difference and $\mathrm{s}_{\bar{\mathrm{d}}}$ represents the standard error of the mean difference. $\mathrm{s}_{\bar{\mathrm{d}}}$ is calculated as;

$$\bar{\mathrm{d}} = \frac{\sum_{i=1}^{n} d_i}{n} \tag{4.4}$$

$$\mathrm{s}_{\bar{\mathrm{d}}} = \frac{\mathrm{s_d}}{\sqrt{\mathrm{n}}} \tag{4.5}$$

Where n represents number of teams.

Using the data provided in Table 4.3, t-statistic is calculated as:

$$\bar{\mathrm{d}} = \frac{3.711}{12} = 0.309$$

$$\mathrm{s}_{\bar{\mathrm{d}}} = \frac{\mathrm{s_d}}{\sqrt{\mathrm{n}}} = \frac{0.225}{\sqrt{12}} = 0.064$$

$$\mathrm{t} = \frac{\bar{\mathrm{d}}}{\mathrm{s}_{\bar{\mathrm{d}}}} = \frac{0.309}{0.064} = 4.761$$

Critical Value for α=0.05 and n=12 is given as:

$t_{\alpha(2),v=n-1} = t_{0.05(2),11} = 1.796$

Decision Rule:

If $|t| \geq 1.796$ then reject H_o otherwise, do not reject H_o

Conclusion:

Since $|4.761| > 1.796$ *($P < 0.001$),* H_o is rejected. The mean difference (d_i) of coefficient of variation of Cycle Times between Phase 2 and Phase 3 considering the actual data from twelve workshops are significantly different.

Table 4.5 : Comparison of Coefficient of Variation of (C/T) in P2 and P3

t-Test results	*Variable 1*	*Variable 2*
Mean	0.489848	0.180557
Variance	0.071903	0.020769
Observation	12	12
t Stat	4.761376476	

We have also tested the data in Excel with same confidence interval (α=0.05). Excel output of t-test results can be seen in Table 4.5. Although in general we can observe a significant change in coefficient of variation of cycle times, the performance of some teams do not confirm with this observation. That is why we have to statistically test our hypothesis to prove the learning and lean effect.

Order Lead Time (LT) (i.e. actual completion time of the last product) is another important KPI of Yamazumi Game. LT measures the speed of inventory and cash flow. For example, from chart of Team 2 and Team 5 (figures 4.22 and 4.23) it is observed that there is a reduction in order lead time in phase 3 compared to phase 2.

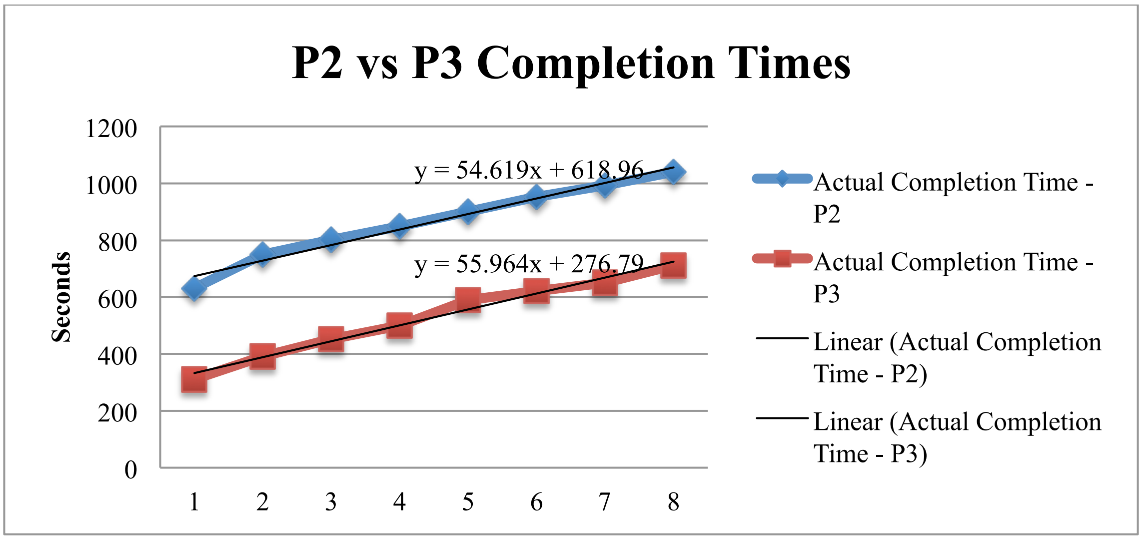


Figure 4.22 : Comparison of Team 2 Performance in P2 and P3

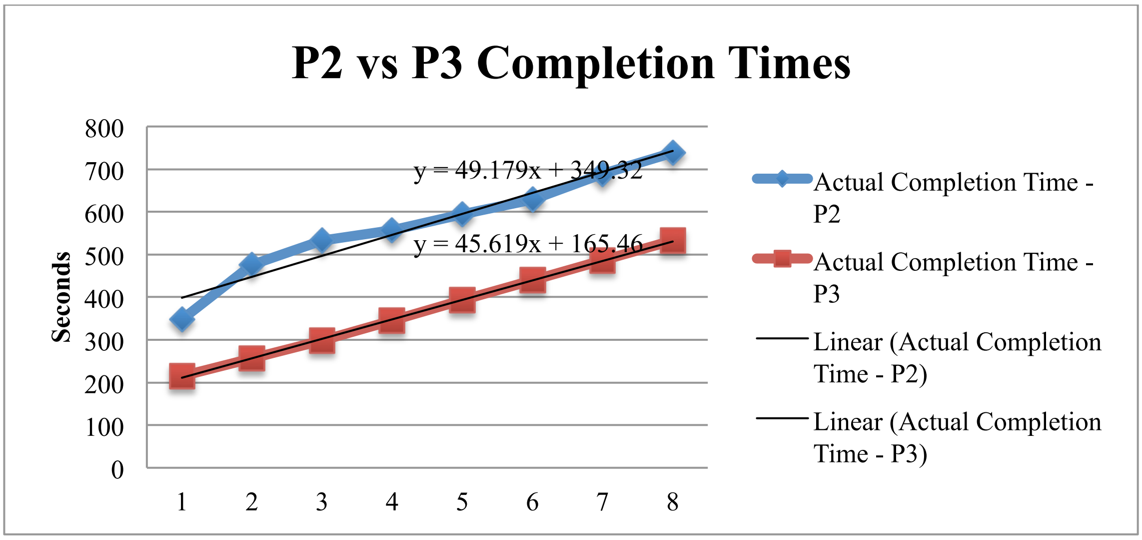


Figure 4.23 : Comparison of Team 5 Performance in P2 And P3

The use of lean methodology improves the system’ performance by not only stabilizing cycle times (i.e. reducing the coefficient of variation of cycle times) but also by reducing the lead time (i.e. the completion time of the entire production order). Nevertheless, we can not say that the performance of Phase 3 is better than Phase 2 for every team. Performance comparison between Phase 2 and Phase 3 are very close to each other for Team 3 and Team 10 as can be seen from Figure 4.24 and Figure 4.25.

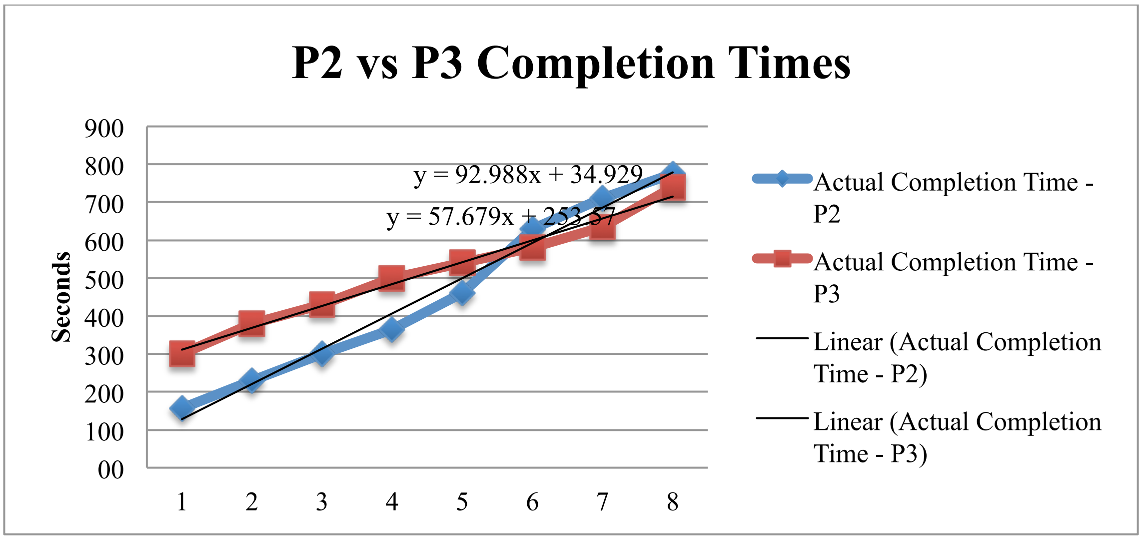


Figure 4.24 : Comparison of Team 3 Completion Times in P2 and P3

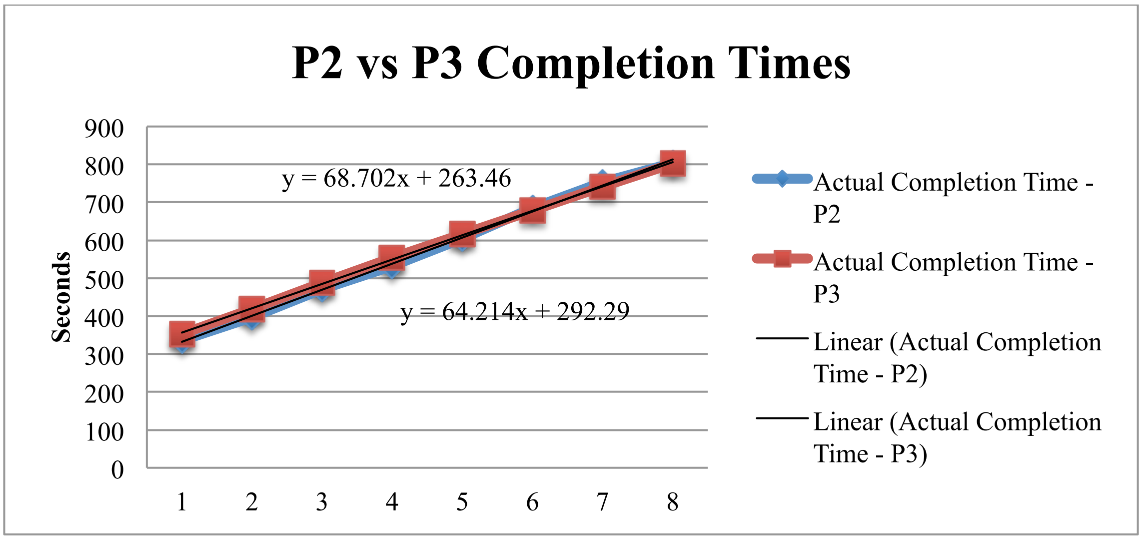


Figure 4.25 : Comparison of Team 10 Completion Times in P2 and P3

Although, lower performance is observed for some teams in Phase 3 in terms of product completion times, we should not compare the performance of teams with respect to a single criterion. The lower lead time does not mean always the better performance. It will be explained in detail on Section 4.2.3.

In this simulation we did not focus on only Lead Time reduction but also Cycle Time reduction and stabilization. Because, accumulated inventories and WIP create non-realistic (smaller than normal) lead time performance. In fact, if the production on the line is continued for sufficiently long time, teams that have high standard deviations on their outputs will encounter with fluctuations on cycle time data. Hence, data have to be controlled by another KPI.

We applied a method comparing the linear regression lines for the cycle times obtained in phases 2 and 3. We compared the linear regression lines that represent the completion times of the products in Phase 2 and Phase 3.

The slope of the line gives us an estimation of cycle time of the line. Even if there are fluctuations on the actual completion times, as shown in Figure 4.26, the regression line estimates the completion time assuming a stable cycle time.

We determined the regression lines for both phases for each team to see how theory performance changes from Phase 2 to Phase 3. For example, coefficient of determination (R^2) is calculated at least 0.92 for Team 12 in Phase 2. This means at least 90% of the variation in completion times can be explained by the regression equation.

The slopes of the regression lines of completion times in phases 2 and 3 for 12 teams, which are reported in Table 4.7, are compared using the paired t test. The slope of lines is decreasing from Phase 2 to Phase 3. This effect can also be observed in Figure 4.26, which reports the regression lines for Team 6.

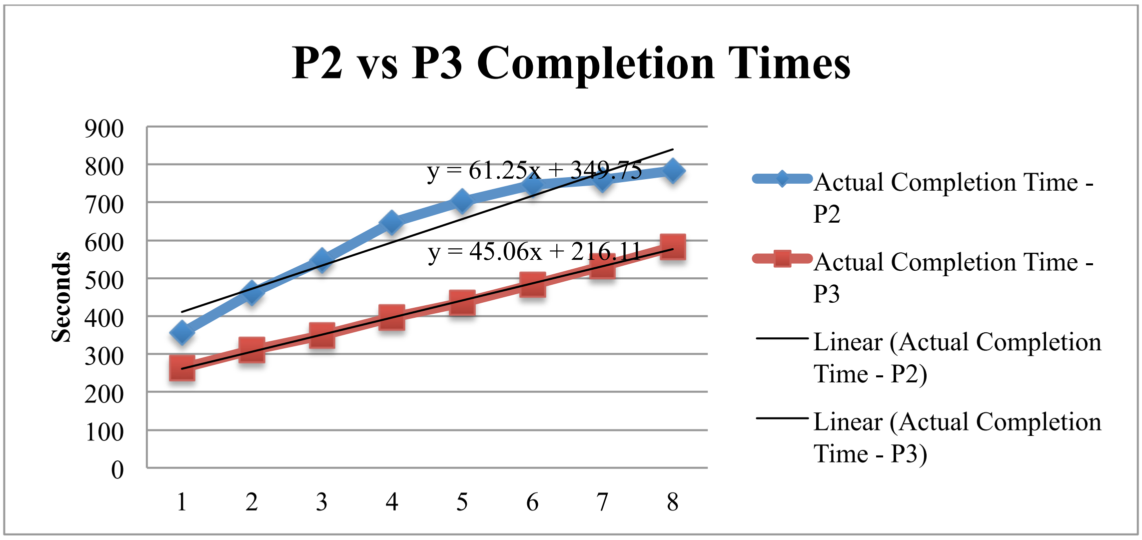


Figure 4.26 : Regression Lines of Team 6 in P2 and P3

If slope of the lines is decreased from Phase 2 to Phase 3, it can be stated that, cycle time is decreasing by using Lean Methodology. As it can be stated before, cycle time reduction is not the only one indicator proving performance improvement effect of lean. Customer demand detects takt time value and thus cycle time of line is determined.

From table 4.6, we see that the performance of each teams in Phase 3 is not always better than Phase 2.

Table 4.6 : Comparison of Slope of Regression Lines (CT_{LR}) in P2 and P3

Team i	*Phase 2 slope*	*Phase 3 slope*	*Difference (d_i)*
1	56.49	49.00	7.49
2	54.62	55.96	-1.35
3	92.99	57.68	35.31
4	53.94	50.90	3.04
5	49.18	45.62	3.56
6	61.25	4506	16.19
7	68.37	48.92	19.45
8	66.92	66.98	-0.06
9	71.99	70.86	1.13
10	68.70	64.21	4.49
11	62.79	51.54	11.25
12	44.04	45.38	-1.35
		$\sum_{i=1}^{12} d_i$	99.15
		s_d	3.13

Hence, we test the hypothesis that the lean methodology results in estimated cycle time improvement using paired t-test to compare the slopes of the regression lines in phases 2 and 3, as follows.

$\mathrm{H_0}: \mu_d = 0$

$\mathrm{H_1}: \mu_d > 0$

μ_d represents mean population difference between slope of regression lines between phase 2 and phase 3, $s_{\bar{d}}$ represents standard deviation of differences of 12 teams, and n represents number of teams.

The test statistic for H_o is a t-statistic calculated as:

$$t = \frac{\bar{d}}{s_{\bar{d}}}$$

Where d_i represents the difference between phase 2 and phase 3 of team i, $\bar{d}$ represents the mean difference and $s_{\bar{d}}$ represents the standard error of the mean difference. $s_{\bar{d}}$ is calculated as;

$$\bar{d} = \frac{\sum_{i=1}^{n} d_i}{n}$$

$$s_{\bar{d}} = \frac{s_d}{\sqrt{n}}$$

Using the data provided in Table 4.5, t-statistic is calculated as:

$$\bar{d} = \frac{99.15}{12} = 8.26$$

$$s_{\bar{d}} = \frac{s_d}{\sqrt{n}} = \frac{10.86}{\sqrt{12}} = 3.13$$

t-statistic:

$$t = \frac{\bar{d}}{s_{\bar{d}}} = \frac{8.26}{3.13} = 2.63$$

Critical Value:

$$t_{\alpha(2),v=n-1} = t_{0,05(2),11} = 1.796$$

Decision Rule:

If $|t| \geq 1.796$ then reject H_o otherwise, do not reject H_o

Conclusion:

Since $|2.63| > 1.796$ *(P < 0.001)*

We reject H_o and conclude that the slope of the regression line in Phase 2 is greater than the one in Phase 3. Table 4.7 reports the t test results by Excel for 95% confidence interval.

Table 4.7 : Comparison of CT_{LR} in P2 and P3

t-Test results	*Variable 1*	*Variable 2*
Mean	62.60515873	54.3422619
Variance	163.9445175	78.52863134
Observation	12	12
t Stat	2.635466659	

Slope of the regression line is one of the most effective KPIs of Yamazumi Game. This data gives us not only stabilized cycle time but also a better estimation of completion times of products.

4.2.2.2 Efficiency Rate of Teams

Number of defective products per production lot and the labor time spent for the production lot are used to define one of the most important KPIs used to evaluate the efficiency of the teams working on the assembly line. This KPI is named as the labor time per quality product (QPT) and calculated as follows:

$$\text{QPT} = \frac{\text{Throughput Time} * \text{Number of Workers}}{\text{Total Number of Quality Products}} \tag{4.6}$$

Labor time is calculated by multiplying throughput time with the number of workers on the assembly line. Throughput time refers to the completion time of the last product in the production lot and quality product refers to a non-defective product that conforms with instructions manual of the product.

Table 4.8 : Comparison of Efficiency Rates for P2 and P3 for Team 1

Key data for performance rate calculation for team 1	***Phase 2***	***Phase 3***
Number of workers	5	5
Number of products per produced	8	8
Number of defective products	5	3
Throughput time	730s	538s
Labor time per quality product (QPT)	1216.7s	538.0s

Clearly, lower QPT means higher team efficiency. Table 4.8 shows the key data used to calculate the efficiency rate for Team 1 in Phases 2 and 3.

Table 4.9 reports QPTs of all 12 teams in Phases 2 and 3. We perform a paired t test to statistically confirm that the efficiency of teams has been improved in Phase 3 (i.e. mean QPT for Phase 2 is greater than mean QPT for Phase 3). If this is confirmed, this indicates that the use of lean tools improves the performance of the teams.

Table 4.9 : Comparison of QPT values in P2 and P3

Team i	Phase 2 QPT	Phase 3 QPT	Difference (d_i)
1	1216.7	538.0	678.7
2	1735.0	712.0	1023.0
3	1162.5	925.0	237.5
4	1041.7	603.0	438.7
5	923.8	443.3	480.4
6	3915.0	485.8	3429.2
7	632.0	326.9	305.1
8	1009.2	505.6	503.6
9	1530.0	692.5	837.5
10	1003.8	572.9	430.9
11	807.0	455.0	352.0
12	1084.5	392.1	692.4
		$\sum_{i=1}^{12} d_i$	9408.8
		s_d	863.7

We can define a mean population difference, *μd*. as a test the null hypothesis, We have applied paired t-test to compare the data in table 4.9, as follows:

$H_0: \mu_d = 0$

$H_1: \mu_d > 0$

μ_d represents the mean population difference between QPT of phase 2 and phase 3, $s_{\bar{d}}$ represents standard deviation of differences of 12 teams, n represents total number of teams.

The test statistic for H_o is a t-statistic calculated as:

$$t = \frac{\bar{d}}{s_{\bar{d}}}$$

Where d_i represents the difference of QPT between phase 2 and phase 3 of team i, $\bar{d}$ represents the mean difference and $s_{\bar{d}}$ represents the standard error of the mean difference. $s_{\bar{d}}$ is calculated as;

$$\bar{d} = \frac{\sum_{i=1}^{12} d_i}{12}$$

$$s_{\bar{d}} = \frac{s_d}{\sqrt{n}}$$

$$\bar{d} = \frac{9408.8}{12} = 784.07$$

$$s_{\bar{d}} = \frac{s_d}{\sqrt{n}} = \frac{863.7}{\sqrt{12}} = 249.3$$

t-statistic:

$$t = \frac{\bar{d}}{s_{\bar{d}}} = \frac{784.07}{248.3} = 3.144$$

Critical Value:

$t_{\alpha(2).\ v=n-1} = t_{0.05(2).11} = 1.796$

Decision Rule:

If $|t| \geq 1.796$ then reject H_o otherwise, do not reject H_o

Conclusion:

Since $|3.144| > 1.796$ *(P < 0.001)*, H_0 is rejected. Therefore, we can conclude that the mean labor time per quality product in Phase 2 are bigger than those in Phase 3 based on the QPTs from 12 workshops where Yamazumi Game is played.

We have also applied Paired t-test (two samples with unequal variances) on Excel to compare the data of efficiency rates. t-test results by Excel for 95% confidence interval can be seen in Table 4.10.

Table 4.10 : t-test Results for QPT Comparison of Phases 2 and 3

t-Test results	*Variable 1*	*Variable 2*
Mean	1338.419444	554.3472222
Variance	745893,6524	26510.62196
Observation	12	12
t Stat	3.144737337	

4.2.3 Comparison of Phase 3 to Ideal State

In earlier sections, we statistically showed the learning effect of Yamazumi Game and the improvement effect of using lean methodologies. In this section, we compare the performance of Phase 3 (i.e. the improved phase using lean concepts) to the ideal performance in order to see how far the performance obtained in Phase 3 is from the ideal state.

The ideal state is defined as the use of an ideally balanced assembly line for the LEGO product used in Yamazumi Game. In Phase 3, the takt time is calculated as 49 seconds and the participants assigned the tasks to workstations such that total task time assigned to a workstation does not exceed 49 seconds takt time. Ideal state is designed by assigning jobs to line having 49 seconds takt time.

We consider SALBP-1 to balance the assembly line in phase 3. SALBP-1 model aims to minimize the number of stations (Scholl and Becker, 2006). For line balancing, the technological precedence diagram has to be considered when assigning the tasks to workstations. Details regarding technological precedence diagram is given in section 4.2.3.1

4.2.3.1 Technological Precedence Diagram

Proplanner® software is used for creating Technological Precedence Diagram (TPD) for the LEGO model used in Yamazumi Game sessions and for assigning tasks to the workstations.

Table 4.11 : Description and Durations of Tasks

Task No	*Description*	*Seconds*
1	Back Wheel Rod Prep.	9
2	Connection Rod Prep.	10
3	Backside Protection	9
4	Backside Covering	15
5	Backside Top Covering	12
6	Back lamp Holder Prep.	6
7	Cabin Sides and Steering Prep.	8
8	Cabin Holder Prep.	3
9	Headlamp Assembling	5
10	Back lamp Preparation	12
11	Front Wheel Rod Prep	7
12	Bumper Assembling	7
13	Loader Holder	4
14	Loader Covering	3
15	Loader Prep.Right Side	10
16	Loader Prep. Left Side	18
17	Ladle assembling	3
18	Cabin Prep.	6
19	Tyre Prep.	13
20	Back lamp Assembling	7
21	Backside-Front side Assembling	9
22	Loader Assembling	5
23	Tyres Assembling	11
24	Cabin Assembling	6
25	Siren Assembling	4
26	Exhaust Assembling	4
27	General Control	10

The tasks required for the assembly of the product and the task times are listed Table 4.11. The detailed assembling procedures of these tasks can be found in Appendix A

Predecessors table (see Table 4.12) are used to create technological precedence diagram. It is used to determine the importance ranking of the tasks.

Table 4.12 : Precedessors of Tasks

Task No	*Description*	*Predecessors*							
1	Back Wheel Rod Prep.								
2	Connection Rod Prep.	1							
3	Backside Protection	2							
4	Backside Covering	3							
5	Backside Top Covering	4							
6	Back lamp Holder Prep.	5							
7	Cabin Sides and Steering Prep.	5							
8	Cabin Holder Prep.	5							
9	Headlamp Assembling	5							
10	Back lamp Preparation	7							
11	Front Wheel Rod Prep								
12	Bumper Assembling	11							
13	Loader Holder	12							
14	Loader Covering	13							
15	Loader Prep.Right Side								
16	Loader Prep. Left Side	15							
17	Ladle assembling	16	14						
18	Cabin Prep.	6	7	8	9				
19	Tyre Prep.	1	11	21					
20	Back lamp Assembling	10	6						
21	Backside-Front side Assembling	2							
22	Loader Assembling	14							
23	Tyres Assembling	19	21						
24	Cabin Assembling	6	7	8	9	18			
25	Siren Assembling	18							
26	Exhaust Assembling	6							
27	General Control	17	20	22	24	26	25	21	23

By entering the predecessors information of tasks into Proplanner software, TPD is drawn, which is shown in Figure 4.27. For a detailed view, see Appendix I

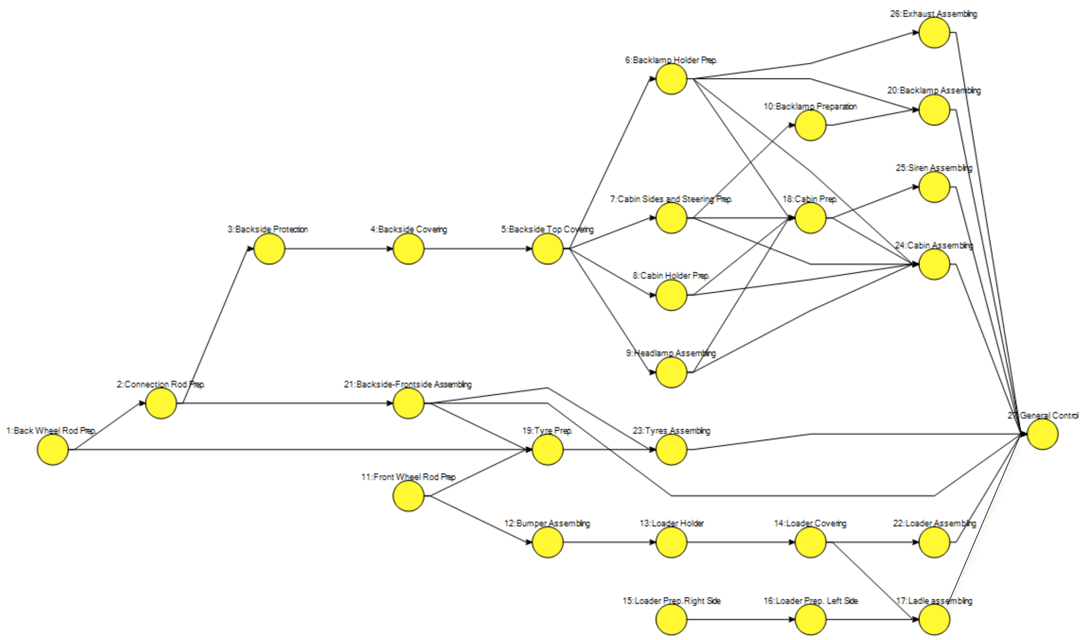


Figure 4.27 : TPD of Tasks by Proplanner®

After determining the technologic precedence diagram where each task is represented by a node, the positional weights are calculated considering the task times. Calculation of positional weights is important to assign task elements (Scholl and Becker, 2006).

4.2.3.2 Task Assignment in the Ideal State

A feasible line balance is defined as the assignment of right jobs to the right stations (Boysen, et al., 2006). In Yamazumi Game, the instructor gives the participants the customer order information and the available shift time to produce the customer order. This information is used to calculate the Takt Time. The cycle time to complete the work at each station should be ideally equal to the takt time although in practice it is usually set slightly less than the takt time because of possible process disruptions that may cause delays or bottlenecks on the line.

In phase 3, after the calculation of takt time, the participants are asked to consider this takt time and assign the tasks to the workstations with the aim of minimizing the number of stations. This approach complies with the Toyota Production System line organization and lean methodologies (Monden, 1983).

In phase 3, the participants are asked to do the task assignment in such a way that the total process time for the last station on the assembly line is minimized or the idle time is maximized. A person who acts as a team leader is assigned to the last station having the maximum idle time. In his idle time, the team leader is responsible of helping other workers on the line in case any problem occurs. This would reduce the fluctuations on actual task processing times, and as a result minimize the standard deviation of cycle times (Duggan, 2013).

We determine an imaginary shift time and customer demand that will create a takt time which requires a non-integer valued number of stations. This will result in an assembly line with the last workstation having some idle time during which the team leader can control the other workstations to see if everything goes smoothly.

The aim of using a team leader with idle time is to improve the efficiency of the line by eliminating non-value added works. The ultimate aim is to eliminate the work assigned to the last workstation and creates a line that has one workstation less (Liker, 2004)

4.2.3.3 Calculation of Takt Time and Number of Stations

The takt time (TT) and the number of workstations required are calculated as follows:

$$\mathrm{TT} = \frac{\text{Dedicated Time (shift, day, month etc.)}}{\text{Customer Demand for Dedicated Time (shift, day, month etc.)}} \tag{4.7}$$

$$\text{Number of Workers (Stations)} = \frac{\text{Total Process Time per Unit}}{\text{Takt Time}} \tag{4.8}$$

In the hypothetical scenario for the Yamazumi game, the customer demand is set to 550 units of product and the shift time is 450 minutes, thus the takt time is calculated as:

$$TT = \frac{450\, minutes * 60\, seconds/minutes}{550\, unit\ cars} = 49\, seconds/car$$

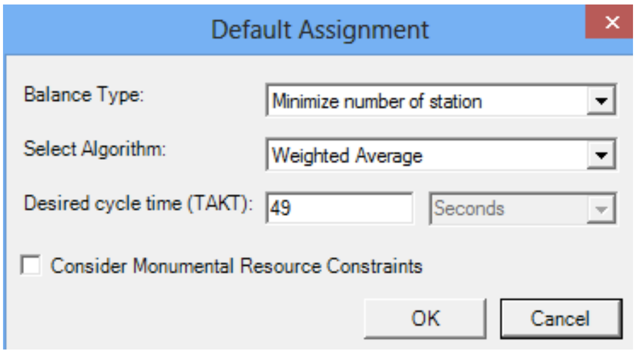
Total process time for one unit of product is determined as 21 seconds. Given this process time and the takt time of 49 seconds, the number of workstations required has a non-integer value as seen below. Hence, the last station on the assembly line will have idle time.

$$\text{Number of Workers (Stations)} = \frac{211\ \text{seconds}}{49\ \text{seconds}} = 4.3$$

The participants are asked to assign the tasks to the 5 workstations considering the predecessor diagram in a way that the cycle time to complete the work at each workstation does not exceed the takt time of 49 seconds and the fifth workstation is assigned the minimum possible workload, i.e. the utilization level of last station is minimized (or the utilization level of the first four stations is maximized).

4.2.3.4 Proplanner Outputs

We determined an ideal task assignment to workstations (i.e. an ideal assembly line) using Proplanner software by choosing the model having the aim of minimizing the number of stations. Proplanner assigns tasks according to SALBP-I that aims to minimize the number of stations and to maximize the utilization of stations except the very last station that is assigned the minimum possible workload.



Default Assignment

Balance Type: Minimize number of station

Select Algorithm: Weighted Average

Desired cycle time (TAKT): 49 Seconds

☐ Consider Monumental Resource Constraints

Figure 4.28 : Input Screen by Proplanner

Takt time (i.e 49 seconds) is entered into the program as well as the predecessors information for the tasks. Proplanner input screen can be seen in Figure 4.28.

Theoretically, if all of tasks were assigned to make minimum utilization, last station utilization would be 40%. Because, the number of stations required is 4.3. Nevertheless, in practice, the tasks may not be assigned as in theory because tasks are not divisible, i.e. a task has to be done entirely in a single station. The task assignment given by Proplanner for 49 seconds of takt time when the algorithm *weighted average* is employed with the aim of minimizing workstations is shown in Table 4.13.

Table 4.13 : Task Assignment by Proplanner

Station 1	*Station 2*	*Station 3*	*Station 4*	*Station 5*
11	16	13	10	23
1	12	5	17	24
15	4	9	20	27
2	21	14	19	
3		6	8	
		22	18	
		7	25	
		26		

The numbers given in Table 4.13 under stations are the task numbers. For example, in the first station of the assembly line, the first task done is task 11, which is followed by tasks 1, 15, 2 and 3, in the given order. One unit of product is completed when task 27 at station 5 is completed. Given this task assignment, the workload of stations (in seconds) is reported in Table 4.14 and pictured in Figure 4.29.

Table 4.14 : Workload of Stations (seconds)

Station-1	Station-2	Station-3	Station-4	Station-5
45	49	47	48	22

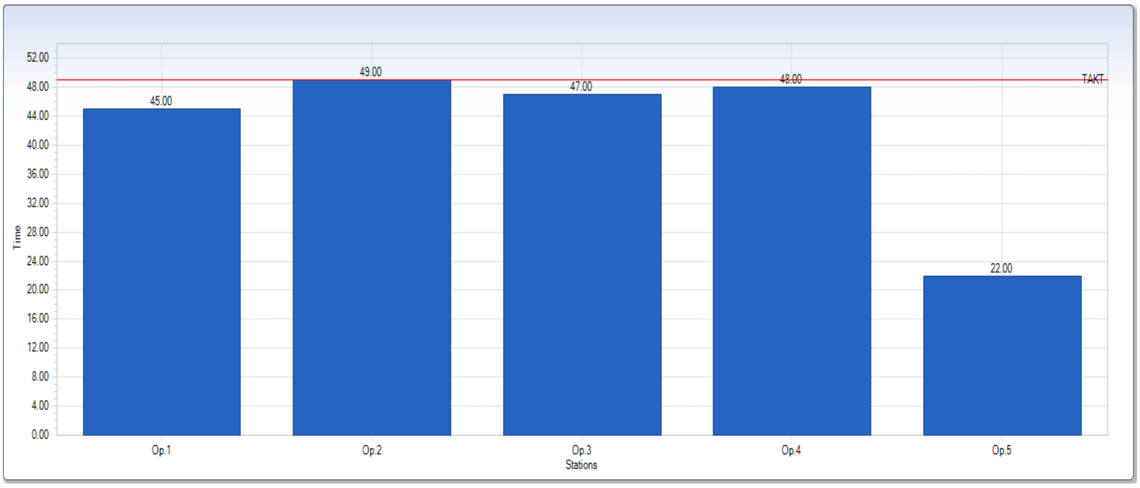


Figure 4.29 : Balancing Station View of Proplanner®

Total balancing delay (Tanyas, 2008) is calculated as:

$$Balancing\ Delay = \frac{Total\ Process\ Time}{Number\ of\ Stations * Takt\ Time} \tag{4.9}$$

$$\text{Balancing Delay} = \frac{211}{5 * 49} = 0{,}8612 = 86.12\%$$

It means, 86,12% of line capacity is used for producing 7630.

The utilization of each station is calculated as below:

$$\%\ utilization = \left(\frac{Assigned\ task\ time\ for\ station}{Takt\ time}\right) 100 \tag{4.10}$$

The percent utilizations of all stations are shown in Table 4.15.

Table 4.15 : Utilization Percentages of Stations

Station 1	*Station 2*	*Station 3*	*Station 4*	*Station 5*
91.8%	100%	95.9%	97.9%	44.9%

Balancing Station View is monitored after Proplanner® run and assigned jobs. It is shown in Figure 4.29. (For detailed assignment see Appendix J)

4.2.3.5 Results and Evaluation

The last evaluation is done between the ideal assembly line and the assembly lines designed by the participants according to lean methodologies in Phase 3.

We compare the task assignment approach of each team to the ideal state of line balancing. Most teams generally calculate correctly the takt time and the number of stations but they cannot assign the tasks as done by Proplanner. We observed three different types of job assignments made by the participants in Phase 3.

Three teams have assigned tasks to the workstations following the order of tasks as given in the instruction manuals. That is, the first few tasks (task 1, task 2, …) are assigned to workstation 1 until its capacity is filled to the maximum extent possible. Then, the remaining unassigned tasks are assigned to workstation 2, then workstation 3, etc. using the similar reasoning until no unassigned task is left. Skipping to the next station while assigning tasks followed up is forbidden.

Table 4.16 : Task Assignment by Considering the Order of Tasks in Instructions Manual

Station-1	*Station-2*	*Station-3*	*Station-4*	*Station-5*
1	5	11	16	21
2	6	12	17	22
3	7	13	18	23
4	8	14	19	24
	9	15	20	25
	10	16		26
				27

For example operator of station-2 has finished task-10 and has to move this sub-assembled part to station-5. One of the rules of Yamazumi Game is assigning jobs assuming existing of a conveyor belt and it is forbidden to bypass next station. Hence, these three teams can not assign jobs appropriately. Task assignment by this approach can be seen in Table 4.16.

In this approach utilization percentages of stations can be seen in table 4.17. The utilization percentage of first four stations are lower than that of last station where the operator is fully utilized, which means that the last operator can not be employed as a team leader.

Table 4.17 : Utilization of Stations Based on Instruction Manual

Station-1	*Station-2*	*Station-3*	*Station-4*	*Station-5*
87.76%	93.88%	63.27%	95.92%	100.00%

Another model is assigning tasks adhering instruction manual without bypassing errors. 4 of 12 teams are assigned jobs this way. In this assignment, tasks are sorted without bypass each other. This type of assignment is shown in Table 4.18.

Table 4.18 : Assignment Matrix of Manually Assignment

Station-1	*Station-2*	*Station-3*	*Station-4*	*Station-5*
1	5	11	15	21
2	6	12	16	22
3	7	13	17	24
4	8	14	18	25
	9	19	23	27
	10	20		

Neverthless utilization of stations is getting higher than previous assignment above and it provides increasing of potential team leader (last station) idle time in this approach. Although idle time of the last station is increasing, it is not closer to ideal state. Utilization of each station is shown in Table 4.19.

Table 4.19 : Utilization of Stations Based on Manually Assignment

Station-1	*Station-2*	*Station-3*	*Station-4*	*Station-5*
87.76%	93.88%	91.84%	97.96%	59.18%

The use of precedence diagram is the third approach used for task assignment. Jobs are assigned by 5 of 12 teams considering RPW algorithm that uses the precedence diagram. While participants drawing TPD, some logical errors caused false task assignments. It is observed that TPD errors caused false task assignment problems. A task assignment obtained by improperly applying the RPW algorithm is shown in Table 4.20 and utilization of each station is shown in Table 4.21.

Although tasks are not properly assigned used on RPW algorithm according to SALBP-1. Assignments are manually checked and corrected by participants.

Table 4.20 : Task Assignment by Improperly Applying RPW

Station-1	*Station-2*	*Station-3*	*Station-4*	*Station-5*
1	5	12	7	20
2	6	13	8	22
3	11	14	9	24
4	15	16	10	25
	19	23	17	26
			18	27
			21	

Table 4.21 : Utilization of Stations of Improperly Used RPW

Station-1	*Station-2*	*Station-3*	*Station-4*	*Station-5*
87.76%	97.96%	87.76%	93.88%	63.27%

It can be argued that this assignment is not close to the ideal state because it causes some task assignment errors; but it is the result of an effort to use learned knowledge as instructor observed. Task assignments made by all teams can be found in Appendix J.

4.2.3.6 Desired Cycle Time (Takt time) Performances

As mentioned above, shortest lead time does not mean the best performance. Customer creates demand as defined the value. Hence, critical point is to synchronizing the output of the line with the customer demand rate. Takt Time (TT) is used for synchronization purpose. The cycle time to complete the work at each station is idealy set to tact time.

Unfortunately, there are some fluctuations on actual cycle times, even being a strict takt time. For this reason, desired cycle time can be stretched out 0.90-0.95 confidence interval (Duggan, 2013). For example, even if desired cycle time of assembly line is 54 or 44, it is applicable for Takt Time. Although, in practise, this fluctuation on desired cycle time is usually prevented by team leaders who called by pulling andon cord, it can be used an advantage for evaluate team performances in this educational game. That is why; we calculate the upper and lower bounds of takt time to compare the performance of the teams follow up formulas below.

$$UB_{TT} = TT + TT * 0.1 \tag{4.11}$$

$$LB_{TT} = TT - TT * 0.1 \tag{4.12}$$

We calculate the upper and lower bounds as;

$$UB_{TT} = 49 + 49 * 0{,}1 = 53.9$$

$$LB_{TT} = 49 - 49 * 0{,}1 = 44.1$$

The estimated cycle times based on actual performance of the teams (represented by the slope of the regression lines that show the completion times as a function of the number of products produced, CT_{LR}) and upper and lower bounds of desired Cycle Times (TT) are compared in Figure 4.30.

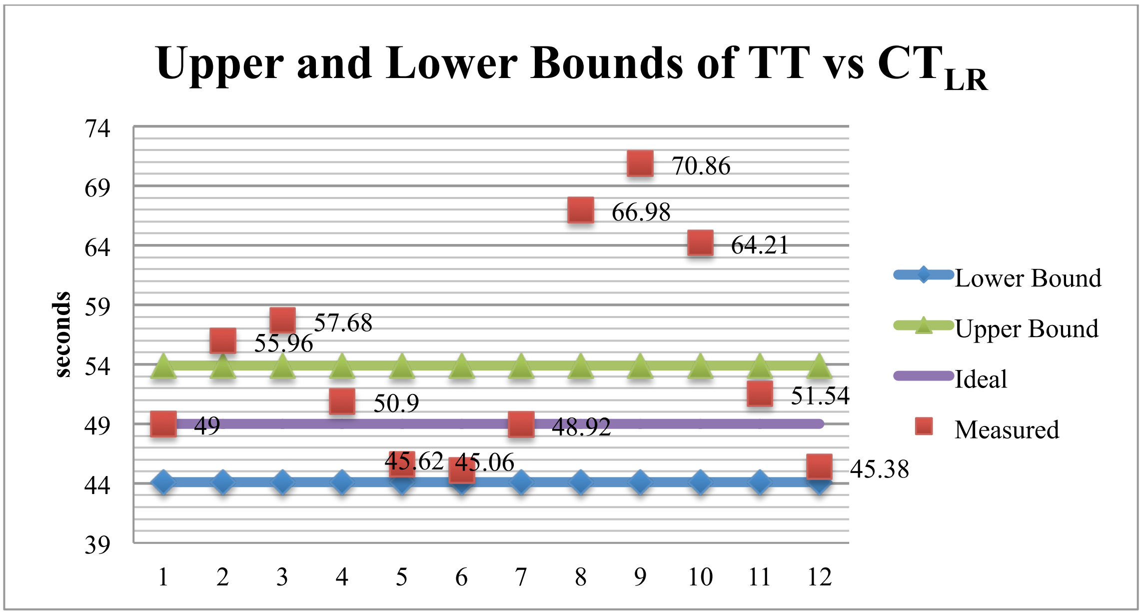


Figure 4.30 : Team Performances and UB-LB for Cycle Time

As shown above, CT_{LR} (slope of the line) 5 of 12 teams are out of upper bound. There are no teams below the lower bound. 7 of 12 teams are within the confidence interval. Team 1 and team 7 perform best with respect to the cycle time. Both teams balance the lines according to SALBP-1. It can not be stated that team 5, team 6 and team 12 performances are better than team 1 and 7 even though their cycle times are lower because this may lead to excess inventory. However, motto of Lean Assembly lines is to work to Takt while producing non-defective products.

5. CONCLUSION

Lean methodology is one of the most popular management approach used in service, healthcare, construction, and especially in manufacturing. The origin of lean methodology was Toyota Motor Company where just-in-time manufacturing, kanban, poka yoke, visual control techniques etc. were first applied. Many lean tools were implemented in Toyota Motor Manufacturing, especially Yamazumi is among the first tools applied in Toyota. Yamazumi contains both industrial engineering and lean applications and it is performed by people who works in assembly line and engineers who are responsible for improving the assembly process.

Experiential learning methodologies provide the efficient learning system called as learning by doing and changes people's minds to improve their real work environment after they have learned some tricks. Moreover experiential trainings are the permanent and sustainable way of knowledge learned in trainings.

At this point we have created an educational game containing both lean and IE concepts, which we call Yamazumi game. In this game, the participants work on assembly lines they create using LEGO parts. The game teaches the participants what are the lean techniques that can be applied and how they can be implemented on assembly lines. The aim is to show the participants the improving effect of lean techniques on assembly line performance.

Yamazumi game has been applied as public workshop or in house training over 100 people who works on different sectors and are different ages for two years.

Yamazumi Game consists of three phases separated into introduction to the educational material, assembly line design without lean concepts, assembly line design with lean concepts. Phase 1, the participants assemble the entire product individually to get used to doing assembly operations; in Phase 2, working as a team, they design an assembly line with workstations that ideally have equal workload, while in Phase 3, they are introduced to lean concepts and then they are allowed to redesign the line.

Moreover, this study analyses the performance of education and lean techniques applied on simulated assembly line by using some game outputs (cycle time, completion time, quality defects) and key performance indicators (KPIs) (coefficient of variations, slope of regression line, labor time per quality product). Phase 2 and phase 3 are compared as performance levels and analysed statistically based on these KPIs. Phase 1 is just analysed about profile of participants and completion times of each participant.

During workshops, in third phase, participants have performed better performance than previous phases. To control the truth of this observations, we statistically analysed performance of teams using game outputs and KPIs. Results show that; the performance of phase 3 on coefficient of variations, slope of regression line, labor time per quality product is better than phase-2. Paired t-test results have compared KPIs statistically and proved the improving effect of using lean concepts in assembly line design.

After Yamazumi game, there are some educational games using lean concepts is being planned to apply and analyse. Some of them use metaphoric approaches instead of simulating lean concepts. Further studies about line balancing game will be designed to create a mixed model assembly line balancing game using lean concepts.

In short, the use of lean approaches improves the performance of the assembly line. Another lesson learnt from this workshop is the productivity and flexibility effect of the teamwork and the team leader on assembly lines.

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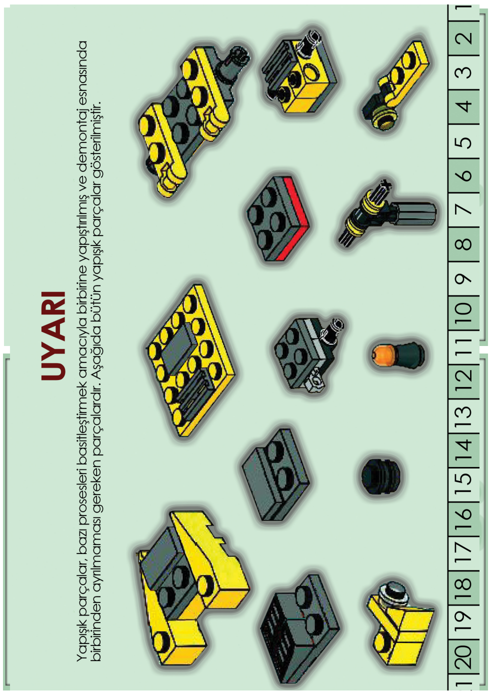
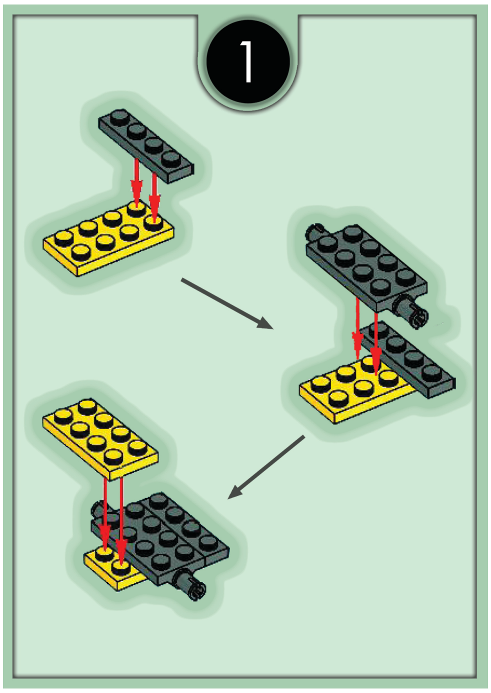
APPENDICES

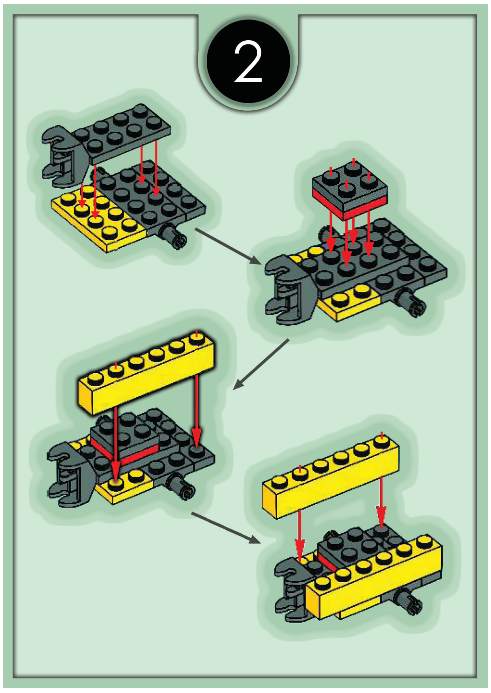
Appendix A- Modified Instructional Manuals

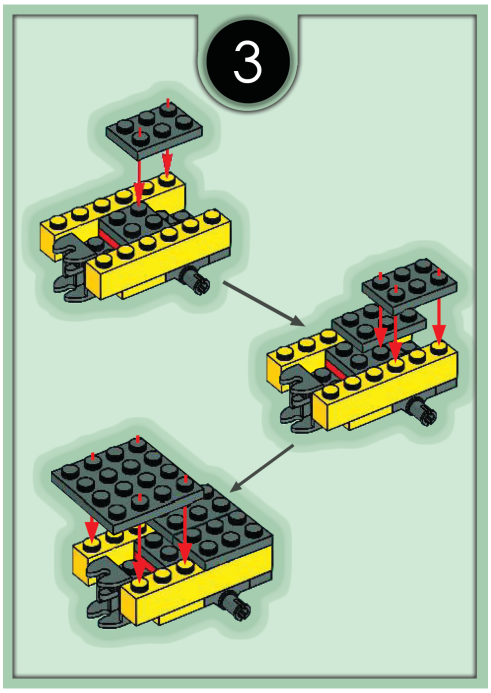


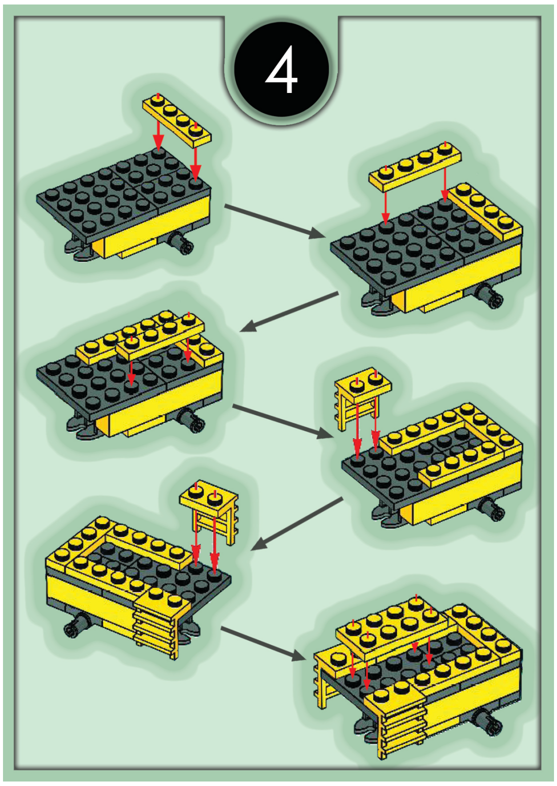
UYARI

Yapışık parçalar, bazı prosesleri basitleştirmek amacıyla birbirine yapıştırılmış ve demontaj esnasında birbirinden ayrılmaması gereken parçalardır. Aşağıda bütün yapışık parçalar gösterilmiştir.





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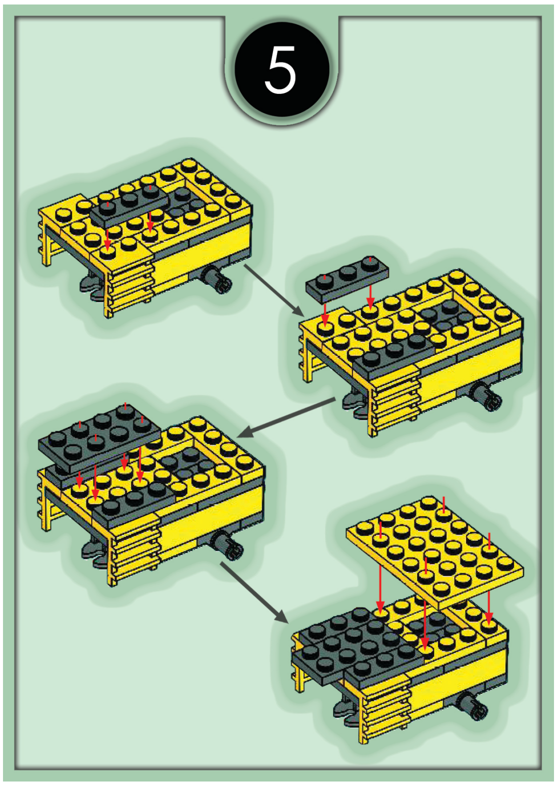
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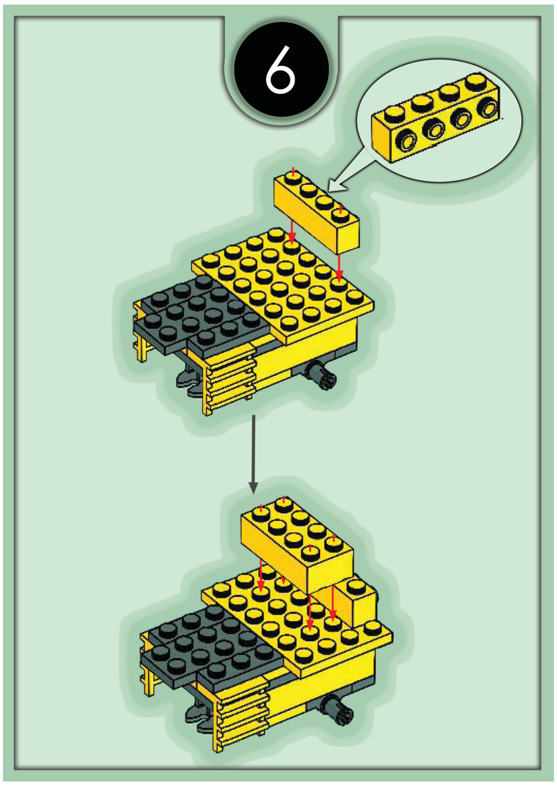
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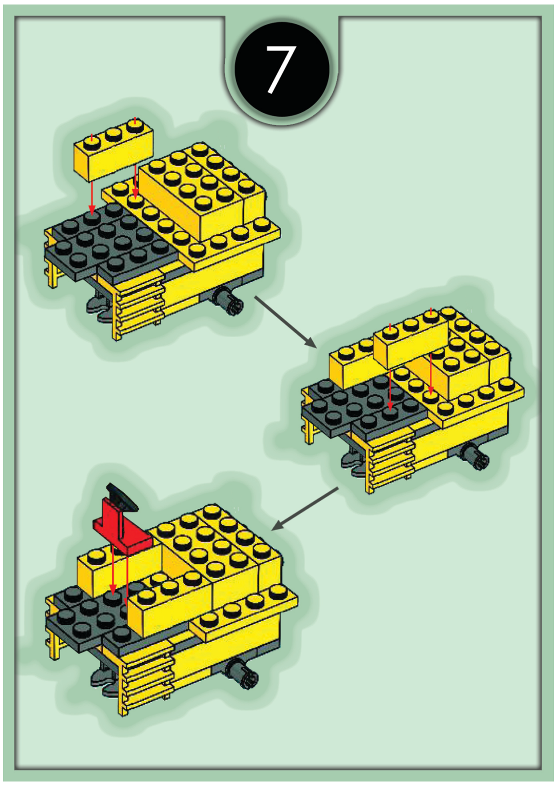
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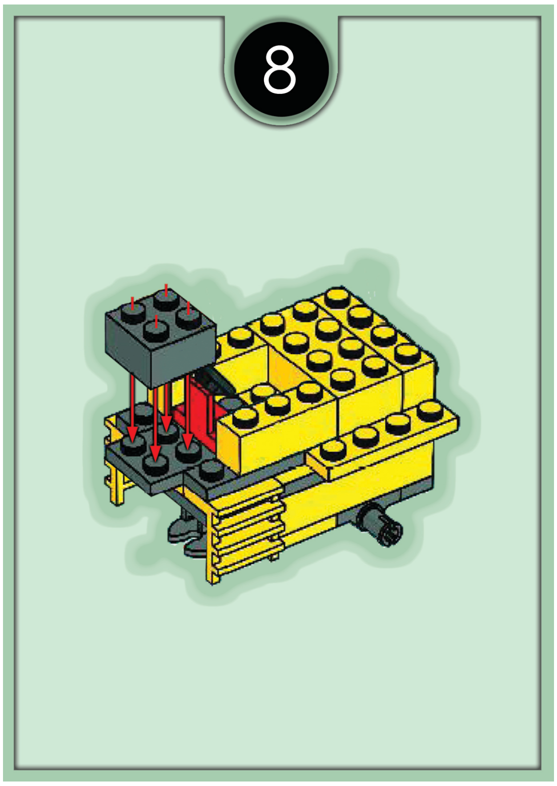
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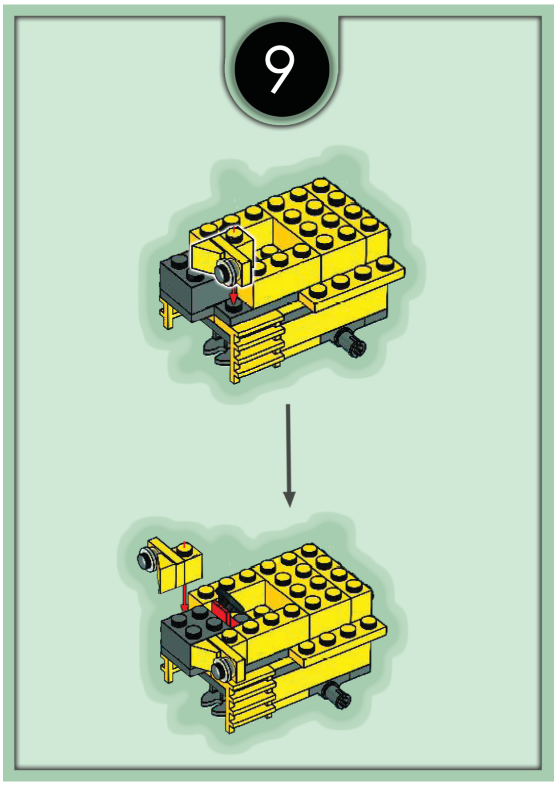
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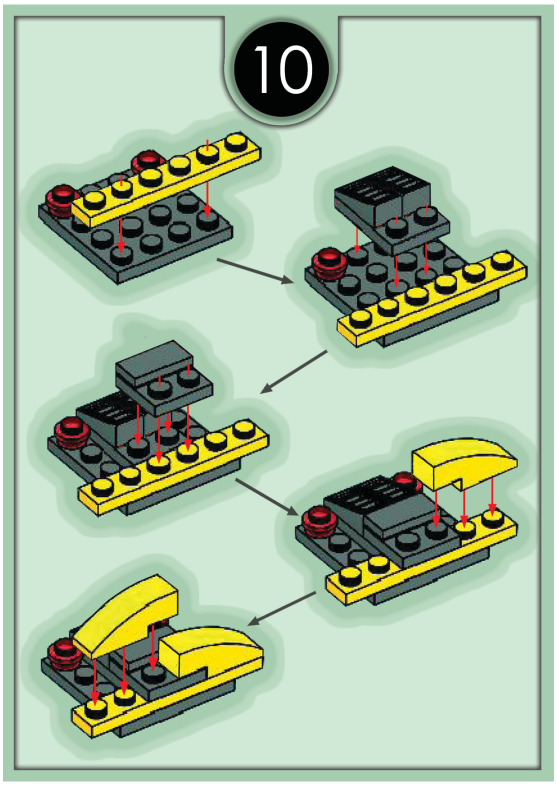
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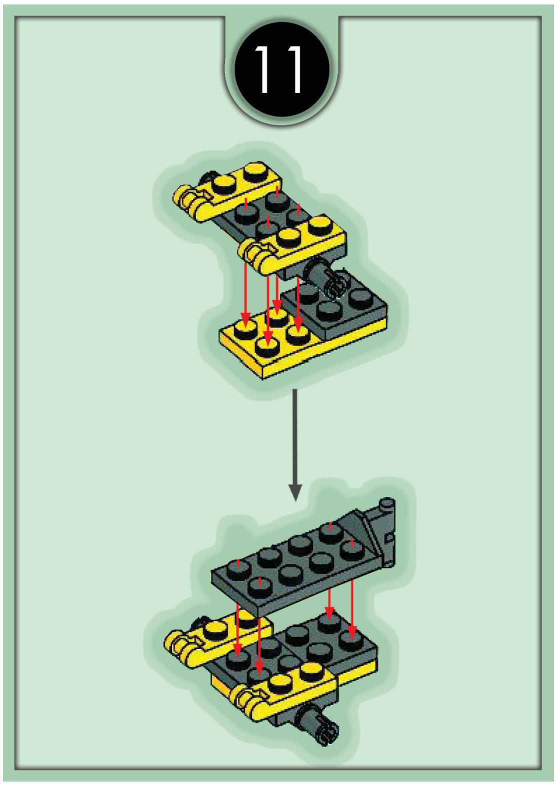
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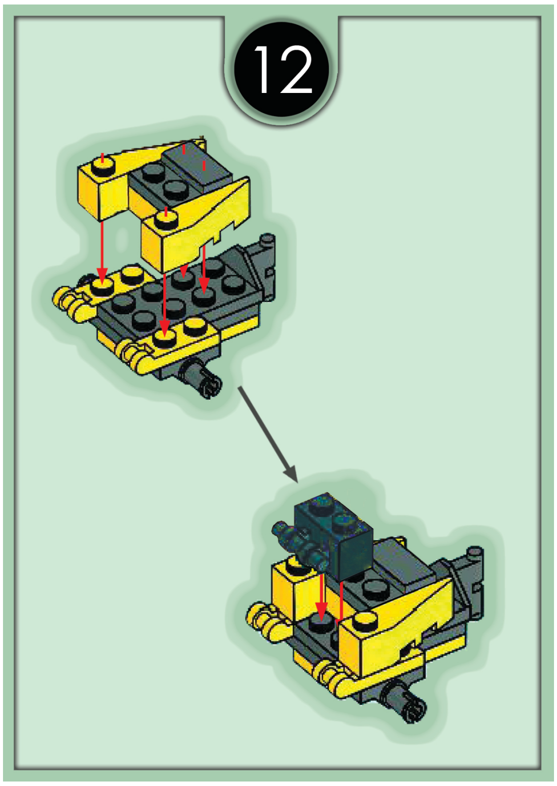
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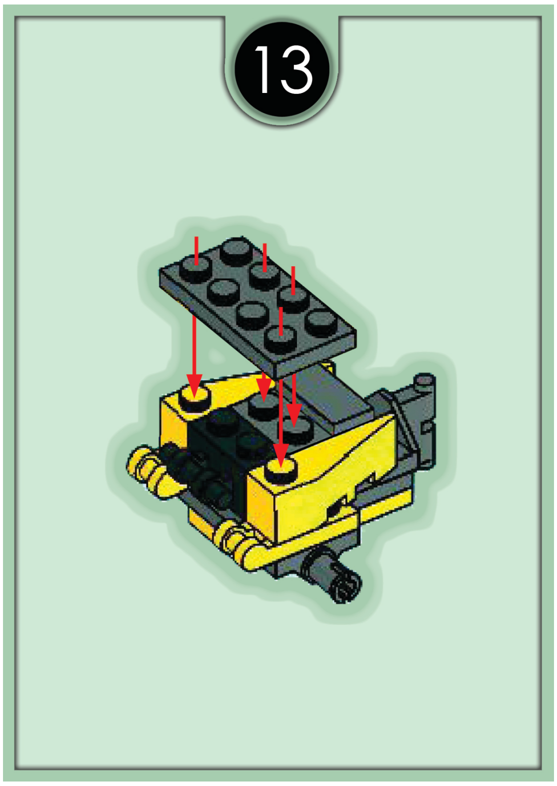
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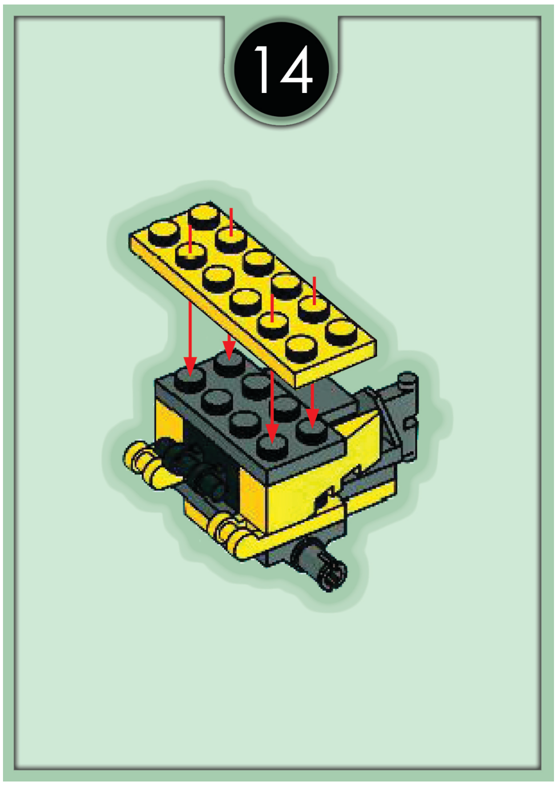
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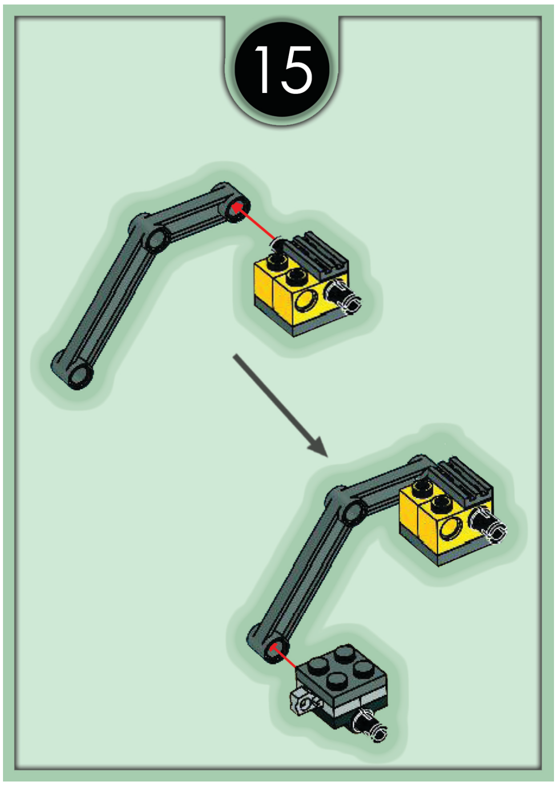
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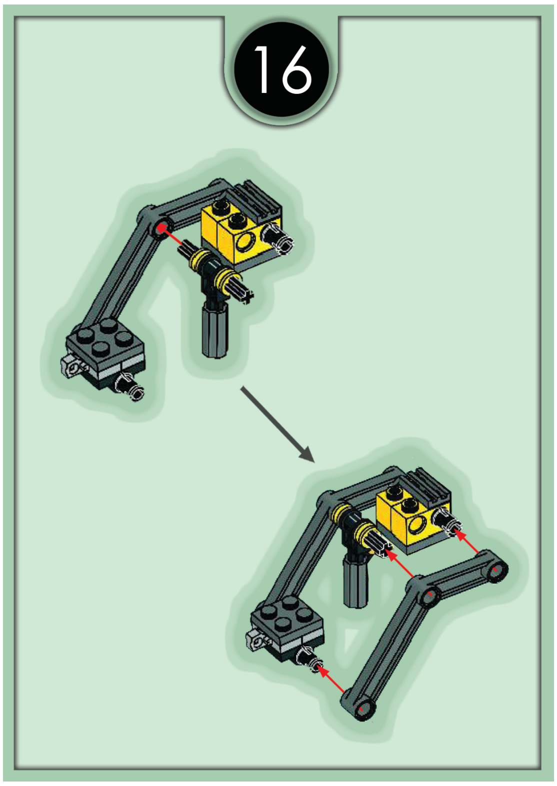
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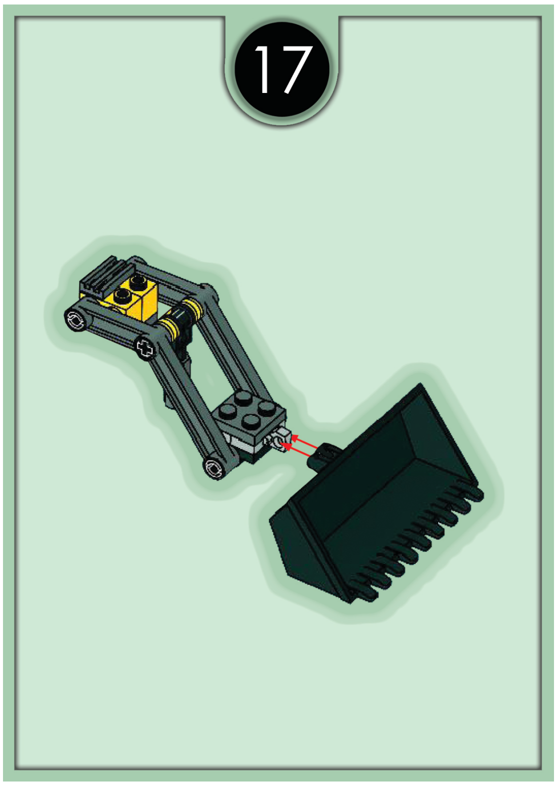
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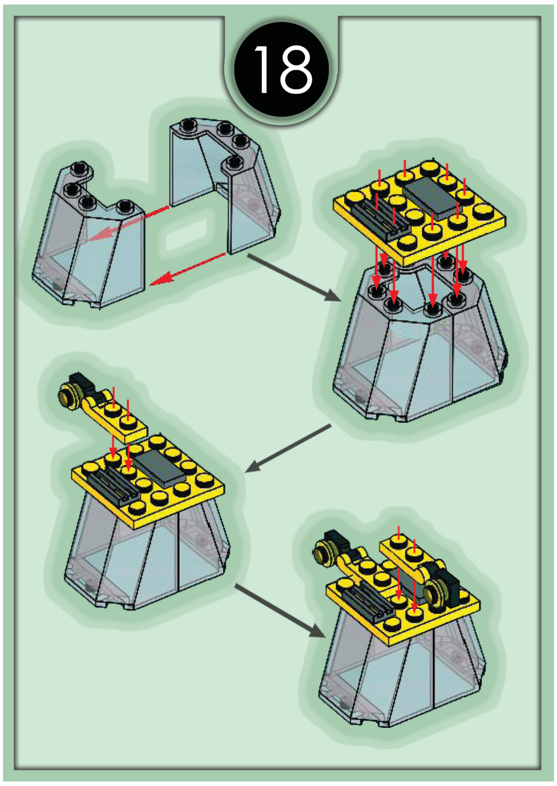
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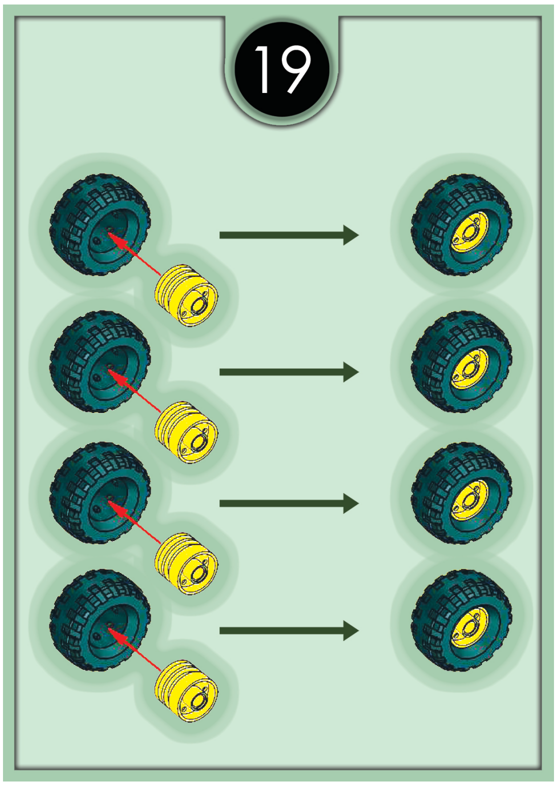
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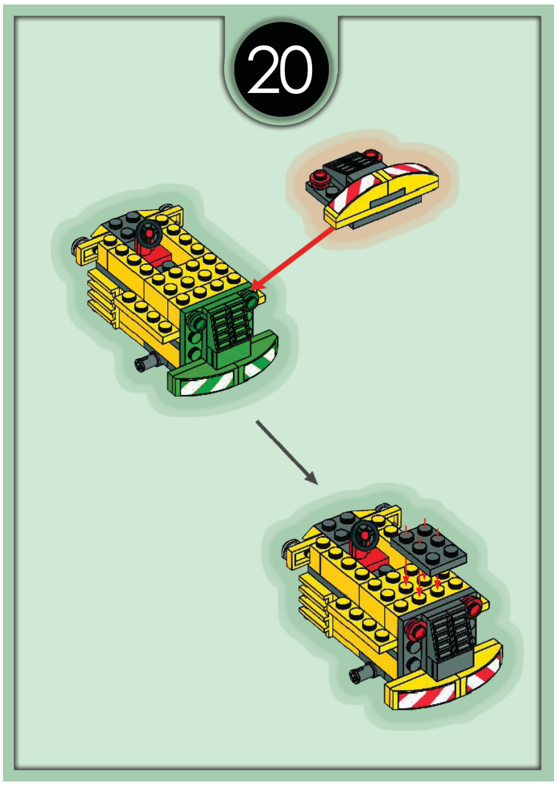
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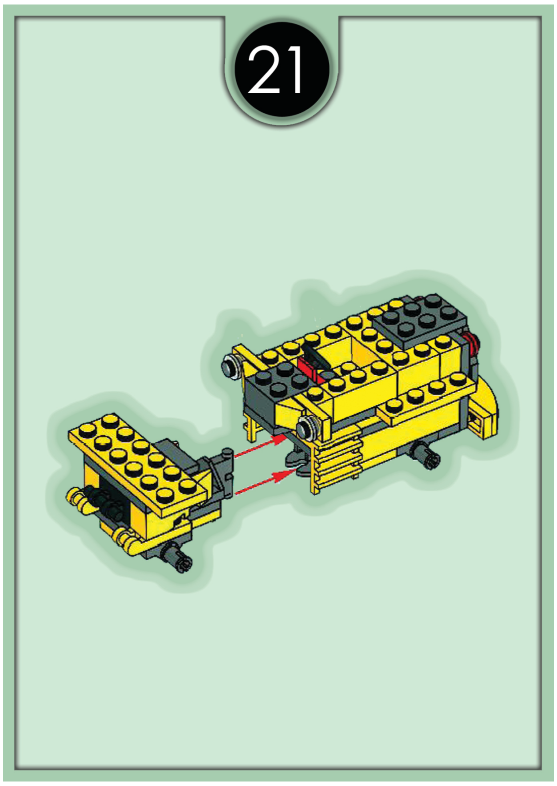
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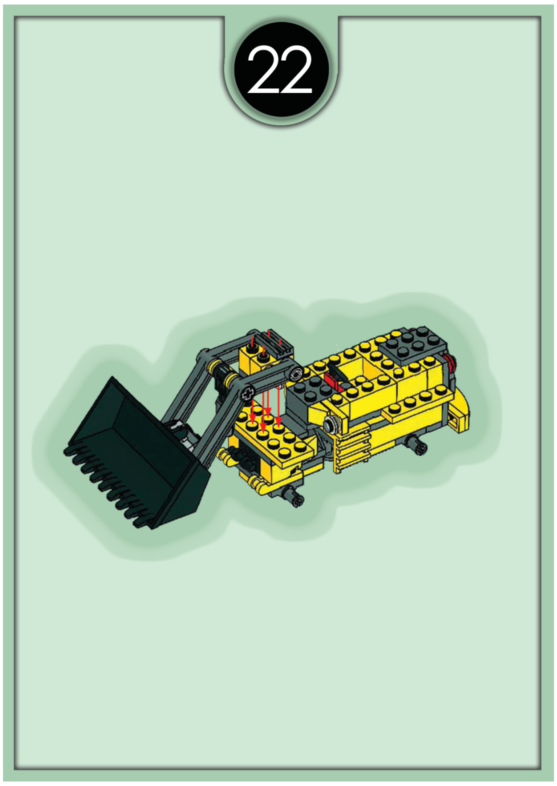
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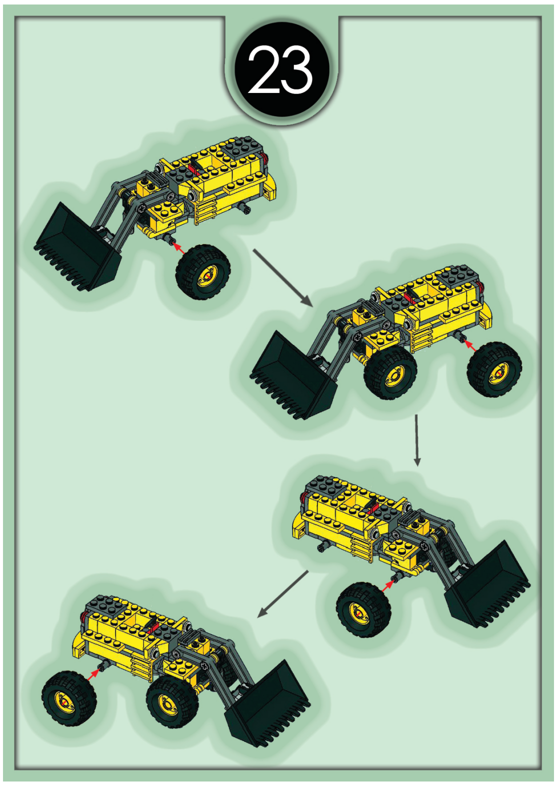
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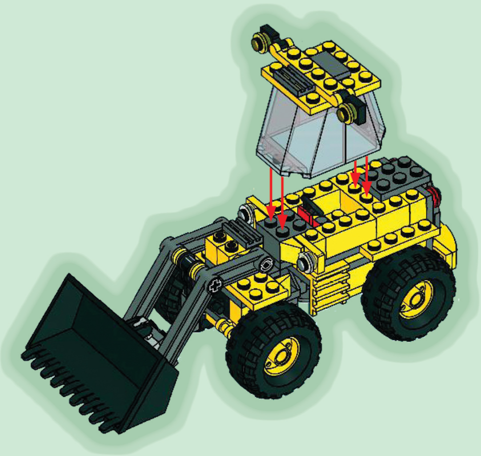

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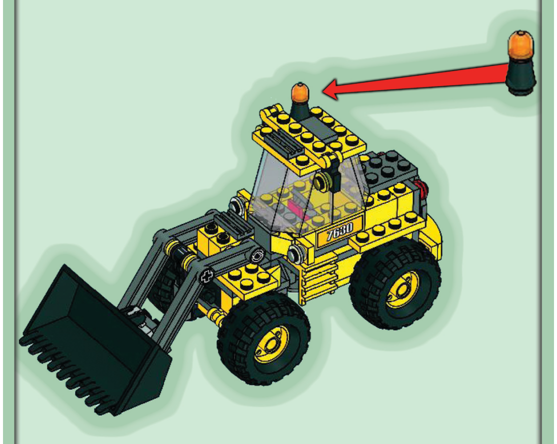

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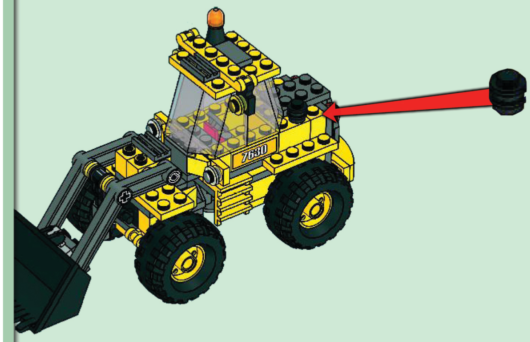

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APPENDIX B.1

Phase-1 Rule Card

This round is designed for understanding the producing procedures of 7630. Please start to produce 7630 by following instruction manuals when chronometer starts. Each card written number on top of it symbolizes one task. Any of tasks could not be divided.

Rules of Phase-1 is shown below:

- Time: There is no time restriction
- You should follow the instruction manual
- When you complete assembling of 7630, please note finishing time on the Table-1.
- If there are any defects on product, please note your finishing time after fix it.
- If you encounter any problems, please note on the Table-2

APPENDIX B.2

Phase-2 Rule Card

In this round, you and your teammates should deploy to build an assembly line to produce eight pieces 7630. In this phase, you have to assign tasks between each others and use these instruction manuals given in Phase-1. Each card written number on top of it symbolizes one task. Any of tasks could not be divided.

- You have to complete eight pieces 7630 in maximum 10 minutes.
- Please follow your discussion session decisions and work on your own station with assigned tasks.
- Even if, Work In Process is defected. it is forbidden to fix it, continue to assemble it
- Even if, you have lost or undelivered parts, continue assembling
- It is strictly forbidden to help you teammates by verbally or physically
- In case of lost or undelivered parts, it is forbidden to demand, continue assembling
- When you complete assembling of 7630, please note, finishing time on the Table-1.
- If you encounter any problems, please note on the Table-2

APPENDIX B.3

Phase-3 Rule Card

In this round, you and your teammates should deploy to build a “Lean” assembly line, working on Lean Tools and conditions to produce eight pieces 7630. In this phase, you have to assign tasks between each other and use not only these instruction manuals, given in Phase-1 but also task columns and Yamazumi boards before discussion session.

Each card written number on top of it symbolizes one task and each column contains same number on cards. Any of tasks could not be divided. Target of your team is to improve your assembly line by using countermeasures of problems occurred on Phase-1.

Customer Demand: 550 unit/day Shift Time: 450 min

- You should work according to customer demands and calculate Takt Time
- During your group discussion please use your materials given (Task times. yamazumi board and instruction manuals) and take based on calculated values (number of stations and takt times)
- Please build a technological precedence diagram before assigning tasks to stations.
- You should assign jobs to minimize last station workload
- If Work In Process is defected. it is forbidden to continue before fixing it. please seek help (pull andon) for your team leader
- If you have lost or undelivered parts, please seek help (pull andon) for your team leader
- In case of problems you and your team leader can help your teammates by verbally or physically
- Please define the work standards before starting to work on your assembly line.
- Design your visual mistake proofing devices (poka yokes) and visual control tools to prevent defects and scraps.
- When you complete assembling of 7630, please note, finishing time on the Table-1.
- If you encounter any problems, please note on the Table-2
- It is strictly forbidden transportation -muda- waste (Production flow should follow up the stations as 1-2-3-4-5)

APPENDIX C

Output Analysis Forms used by Participants in Phase-1. Phase-2 and Phase-3

Phase-1	**1**
Output Times (sn)	
If part is defect (Please Thick)	
Order Lead Time	
Production Lead Time	
Total Process Time	

Phase-2	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Output Times (sn)								
Line Cycle Time (C/T) (Between Products-sn)	0							
Defect Parts (Please Thick)								
Order Lead Time								
Production Lead Time								
Total Process Time								

Phase-2	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Output Times (sn)								
Line Cycle Time (C/T) (Between Products-sn)	0							
Defect Parts (Please Thick)								
Order Lead Time								
Production Lead Time								
Total Process Time								

APPENDIX D

Output Analysis Forms used in Phase-2 and Phase-3

Phase No: 2	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Output Times								
Line Cycle Time (sn)								
Defect Parts								
Summary of Phase-1 for Team-2								
Coefficient of variation of C/T (sn)								
Number of Team Members								
Number of Defect Parts								
Number of Team Leader								
Performance Rate								

Phase No: 3	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Output Times								
Line Cycle Time (sn)								
Defect Parts								
Summary of Phase-1 for Team-2								
Coefficient of variation of C/T (sn)								
Number of Team Members								
Number of Defect Parts								
Number of Team Leader								
Performance Rate								

APPENDIX E

Problem Solving Forms used in Phase-2

	PLAN		DO	CHECK	ACT
Problem No	Problem Occured	Station No	Counter Measures	% Improvement	Standardization Comments
1					
2					
3					
4					
5					
6					
7					
8					

APPENDIX F.1

Output Analysis of Team-1 Phase-2 and Phase-3

Phase-2	1	2	3	4	5	6	7	8
R1 Output Time	**365**	395	425	455	535	620	700	**730**
Line Cycle Time		30	30	30	80	85	80	30
C/T Deviation from Average CT		43	43	43	-7	-12	-7	43
Defect Parts	1	1				1	1	1
Coefficient of variation of C/T (sn)	0.531							
Number of Team Members	5							
Number of Defect Parts	5							
Number of Team Leader	0							

Phase-3	1	2	3	4	5	6	7	8
R1 Output Time	**193**	246	304	352	400	445	492	**538**
Line Cycle Time		53	58	48	48	45	47	46
C/T Deviation from Average CT		-14.4	-19.4	-9.4	-9.4	-6.4	-8.4	-7.4
Defect Parts	1			1	1			
Coefficient of variation of C/T (sn)	0.094							
Number of Team Members	5							
Number of Defect Parts	3							
Number of Team Leader	1							

APPENDIX F.2

Output Analysis of Team-2 Phase-2 and Phase-3

Phase-2	1	2	3	4	5	6	7	8
R1 Output Time	**631**	750	802	848	901	952	993	**1041**
Line Cycle Time		119	52	46	53	51	41	48
C/T Deviation from Average CT		7.2	74.2	80.2	73.2	75.2	85.2	78.2
Defect Parts				1	1	1	1	1
Coefficient of variation of C/T (sn)	0.460							
Number of Team Members	5							
Number of Defect Parts	5							
Number of Team Leader	0							

Phase-3	1	2	3	4	5	6	7	8
R1 Output Time	**311**	391	453	500	590	621	651	**712**
Line Cycle Time		80	62	47	90	31	30	61
C/T Deviation from Average CT		-17.8	0.2	15.2	-27.8	31.2	32.2	1.2
Defect Parts	1	1	1					
Coefficient of variation of C/T (sn)	0.401							
Number of Team Members	5							
Number of Defect Parts	3							
Number of Team Leader	1							

APPENDIX F.3

Output Analysis of Team-3 Phase-2 and Phase-3

Phase-2	1	2	3	4	5	6	7	8
R1 Output Time	**157.0**	230.0	300.0	365.0	460.0	630.0	710.0	**775.0**
Line Cycle Time		73.0	70.0	65.0	95.0	170.0	80.0	65.0
C/T Deviation from Average CT		-46.8	-43.8	-38.8	-68.8	-143.8	-53.8	-38.8
Defect Parts	1	1	1	1				
Coefficient of variation of C/T (sn)	0.425							
Number of Team Members	6.0							
Number of Defect Parts	4.0							
Number of Team Leader	0.0							

Phase-3	1	2	3	4	5	6	7	8
R1 Output Time	**300.0**	380.0	430.0	500.0	540.0	580.0	635.0	**740.0**
Line Cycle Time		80.0	50.0	70.0	40.0	40.0	55.0	105.0
C/T Deviation from Average CT		-20.0	10.0	-10.0	20.0	20.0	5.0	-45.0
Defect Parts	1	1		1		1		
Coefficient of variation of C/T (sn)	0.378							
Number of Team Members	5.0							
Number of Defect Parts	4.0							
Number of Team Leader	1.0							

APPENDIX F.4

Output Analysis of Team-4 Phase-2 and Phase-3

Phase-2	1	2	3	4	5	6	7	8
R1 Output Time	**235**	310	384	422	485	505	585	**625**
Line Cycle Time		75	74	38	63	20	80	40
C/T Deviation from Average CT		-28	-27	9	-16	27	-33	7
Defect Parts	1			1	1	1	1	
Coefficient of variation of C/T (sn)	0.414							
Number of Team Members	5							
Number of Defect Parts	5							
Number of Team Leader	0							

Phase-3	1	2	3	4	5	6	7	8
R1 Output Time	**245**	293	342	386	439	491	547	**603**
Line Cycle Time		48	49	44	53	52	56	56
C/T Deviation from Average CT		1	0	5	-4	-3	-7	-7
Defect Parts	1	1		1				
Coefficient of variation of C/T (sn)	0.086							
Number of Team Members	5							
Number of Defect Parts	3							
Number of Team Leader	1							

APPENDIX F.5

Output Analysis of Team-5 Phase-2 and Phase-3

Phase-2	1	2	3	4	5	6	7	8
R1 Output Time	**348**	476	532	557	595	629	689	**739**
Line Cycle Time		128	56	25	38	34	60	50
C/T Deviation from Average CT		-58.4	13.6	44.6	31.6	35.6	9.6	19.6
Defect Parts	1			1		1	1	
Coefficient of variation of C/T (sn)	0.612							
Number of Team Members	5							
Number of Defect Parts	4							
Number of Team Leader	0							

Phase-3	1	2	3	4	5	6	7	8
R1 Output Time	**215**	257	299	345	393	439	486	**532**
Line Cycle Time		42	42	46	48	46	47	46
C/T Deviation from Average CT		1	1	-3	-5	-3	-4	-3
Defect Parts	1	1						
Coefficient of variation of C/T (sn)	0.052							
Number of Team Members	5							
Number of Defect Parts	2							
Number of Team Leader	1							

APPENDIX F.6

Output Analysis of Team-6 Phase-2 and Phase-3

Phase-2	1	2	3	4	5	6	7	8
R1 Output Time	**356**	460	547	647	703	747	760	**783**
Line Cycle Time		104	87	100	56	44	13	23
C/T Deviation from Average CT		-32.8	-15.8	-28.8	15.2	27.2	58.2	48.2
Defect Parts	1	1	1	1	1	1	1	
Coefficient of variation of C/T (sn)	0.603							
Number of Team Members	5							
Number of Defect Parts	7							
Number of Team Leader	0							

Phase-3	1	2	3	4	5	6	7	8
R1 Output Time	**263**	310	350	396	435	482	532	**583**
Line Cycle Time		47	40	46	39	47	50	51
C/T Deviation from Average CT		5.6	12.6	6.6	13.6	5.6	2.6	1.6
Defect Parts	1	1						
Coefficient of variation of C/T (sn)	0.101							
Number of Team Members	5							
Number of Defect Parts	2							
Number of Team Leader	1							

APPENDIX F.7

Output Analysis of Team-7 Phase-2 and Phase-3

Phase-2	1	2	3	4	5	6	7	8
R1 Output Time	**298**	345	443	490	542	632	702	**775**
Line Cycle Time		47	98	47	52	90	70	73
C/T Deviation from Average CT		12.6	-38.4	12.6	7.6	-30.4	-10.4	-13.4
Defect Parts	1			1		1		
Coefficient of variation of C/T (sn)	0.303							
Number of Team Members	5							
Number of Defect Parts	3							
Number of Team Leader	0							

Phase-3	1	2	3	4	5	6	7	8
R1 Output Time	**277**	333	386	437	485	523	573	**627**
Line Cycle Time		56	53	51	48	38	50	54
C/T Deviation from Average CT		-0.6	2.4	4.4	7.4	17.4	5.4	1.4
Defect Parts								
Coefficient of variation of C/T (sn)	0.118							
Number of Team Members	5							
Number of Defect Parts	0							
Number of Team Leader	1							

APPENDIX F.8

Output Analysis of Team-8 Phase-2 and Phase-3

Phase-2	1	2	3	4	5	6	7	8
R1 Output Time	351	467	557	610	680	734	785	**841**
Line Cycle Time		116	90	53	70	54	51	56
C/T Deviation from Average CT		-57.5	-31.5	5.5	-11.5	4.5	7.5	2.5
Defect Parts	1	1	1					
Coefficient of variation of C/T (sn)	0.351							
Number of Team Members	6							
Number of Defect Parts	3							
Number of Team Leader	0							

Phase-3	1	2	3	4	5	6	7	8
R1 Output Time	348	409	466	530	601	677	748	**809**
Line Cycle Time		61	57	64	71	76	71	61
C/T Deviation from Average CT		8.6	12.6	5.6	-1.4	-6.4	-1.4	8.6
Defect Parts								
Coefficient of variation of C/T (sn)	0.105							
Number of Team Members	5							
Number of Defect Parts	0							
Number of Team Leader	1							

APPENDIX F.9

Output Analysis of Team-9 Phase-2 and Phase-3

Phase-2	1	2	3	4	5	6	7	8
R1 Output Time	399	493	566	633	703	769	840	**918**
Line Cycle Time		94	73	67	70	66	71	78
C/T Deviation from Average CT		-14.2	6.8	12.8	9.8	13.8	8.8	1.8
Defect Parts	1			1		1	1	1
Coefficient of variation of C/T (sn)	0.130							
Number of Team Members	5							
Number of Defect Parts	5							
Number of Team Leader	0							

Phase-3	1	2	3	4	5	6	7	8
R1 Output Time	329	412	487	560	630	693	762	**831**
Line Cycle Time		83	75	73	70	63	69	69
C/T Deviation from Average CT		-17.2	-9.2	-7.2	-4.2	2.8	-3.2	-3.2
Defect Parts	1	1						
Coefficient of variation of C/T (sn)	0.087							
Number of Team Members	5							
Number of Defect Parts	2							
Number of Team Leader	1							

APPENDIX F.10

Output Analysis of Team-10 Phase-2 and Phase-3

Phase-2	1	2	3	4	5	6	7	8
R1 Output Time	335	397	471	532	605	685	753	**803**
Line Cycle Time		62	74	61	73	80	68	50
C/T Deviation from Average CT		5	-7	6	-6	-13	-1	17
Defect Parts	1			1		1	1	
Coefficient of variation of C/T (sn)	0.150							
Number of Team Members	5							
Number of Defect Parts	4							
Number of Team Leader	0							

Phase-3	1	2	3	4	5	6	7	8
R1 Output Time	353	418	487	554	617	678	741	**802**
Line Cycle Time		65	69	67	63	61	63	61
C/T Deviation from Average CT		5.6	1.6	3.6	7.6	9.6	7.6	9.6
Defect Parts	1							
Coefficient of variation of C/T (sn)	0.047							
Number of Team Members	5							
Number of Defect Parts	1							
Number of Team Leader	1							

APPENDIX F.11

Output Analysis of Team-11 Phase-2 and Phase-3

Phase-2	1	2	3	4	5	6	7	8
R1 Output Time	376	432	583	587	639	703	801	**807**
Line Cycle Time		56	151	4	52	64	98	6
C/T Deviation from Average CT		19.2	-75.8	71.2	23.2	11.2	-22.8	69.2
Defect Parts	1		1				1	
Coefficient of variation of C/T (sn)	0.835							
Number of Team Members	5							
Number of Defect Parts	3							
Number of Team Leader	0							

Phase-3	1	2	3	4	5	6	7	8
R1 Output Time	287	325	369	415	462	543	587	**637**
Line Cycle Time		38	44	46	47	81	44	50
C/T Deviation from Average CT		19.4	13.4	11.4	10.4	-23.6	13.4	7.4
Defect Parts						1		
Coefficient of variation of C/T (sn)	0.283							
Number of Team Members	5							
Number of Defect Parts	1							
Number of Team Leader	1							

APPENDIX F.12

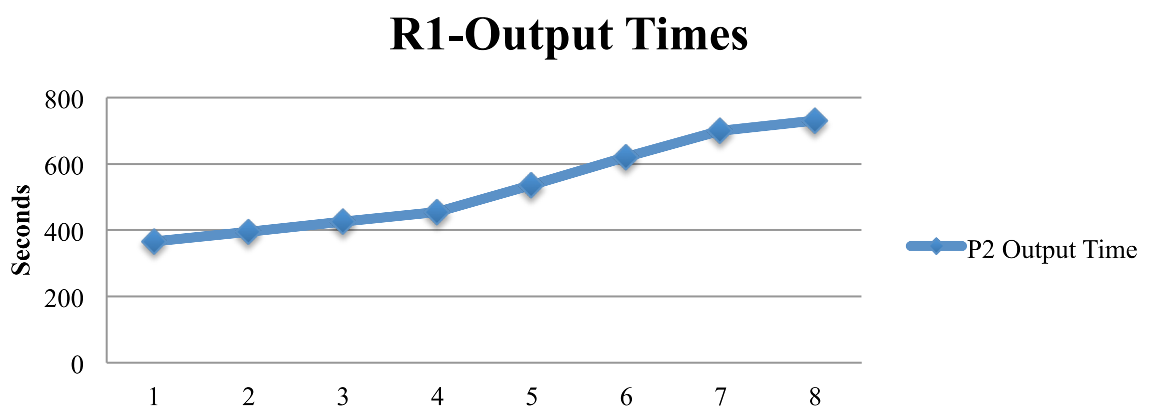
Output Analysis of Team-12 Phase-2 and Phase-3

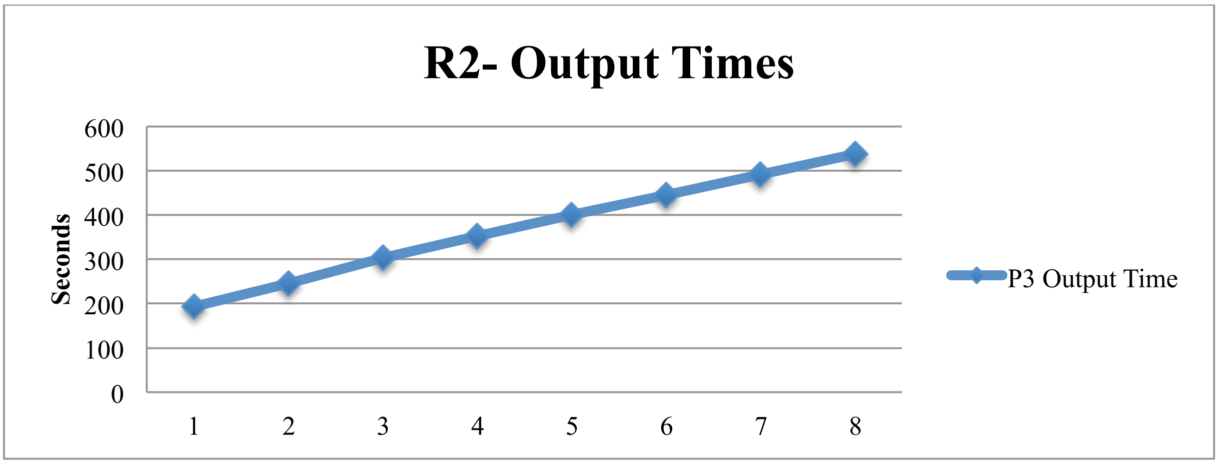
Phase-2	1	2	3	4	5	6	7	8
R1 Output Time	403.0	502.0	570.0	573.0	573.0	688.0	723.0	**723.0**
Line Cycle Time		99.0	68.0	3.0	0.0	115.0	35.0	0.0
C/T Deviation from Average CT		-31.8	-0.8	64.2	67.2	-47.8	32.2	67.2
Defect Parts		1.0	1.0	1.0	1.0			
Coefficient of variation of C/T (sn)	1.066							
Number of Team Members	6.0							
Number of Defect Parts	4.0							
Number of Team Leader	0.0							

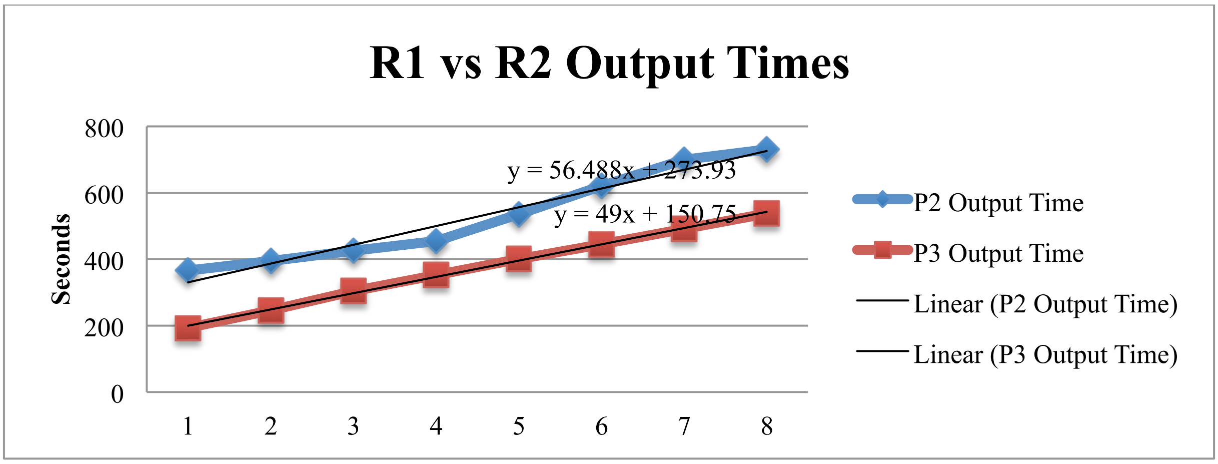
Phase-3	1	2	3	4	5	6	7	8
R1 Output Time	222	273	326	345	372	433	508	**549**
Line Cycle Time		51	53	19	27	61	75	41
C/T Deviation from Average CT		-6.6	-8.6	25.4	17.4	-16.6	-30.6	3.4
Defect Parts						1		
Coefficient of variation of C/T (sn)	0.415							
Number of Team Members	5							
Number of Defect Parts	1							
Number of Team Leader	1							

APPENDIX G.1

Output Analysis Graph of Team-1 (Phase-2 and Phase-3)

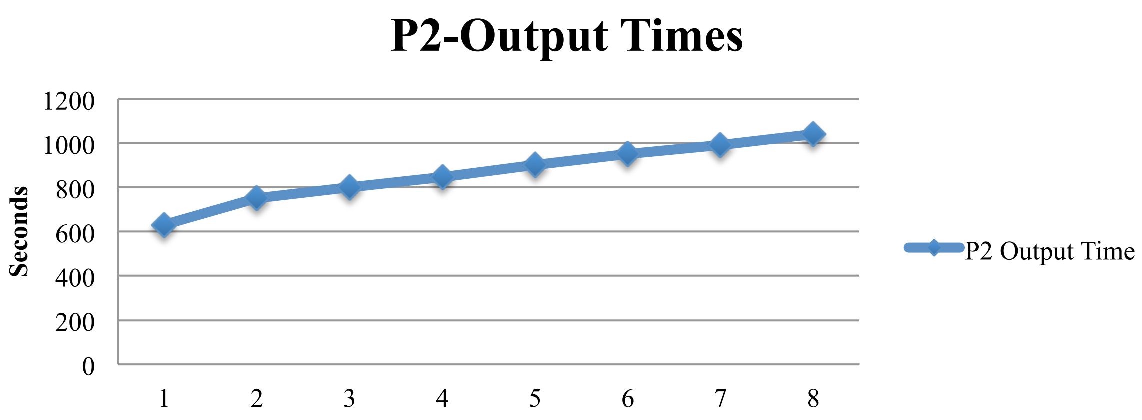


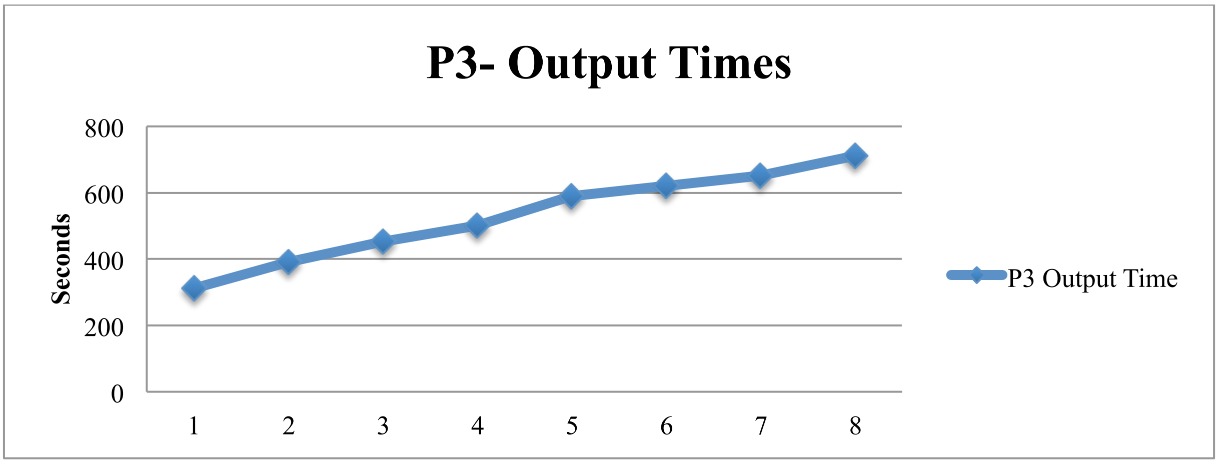


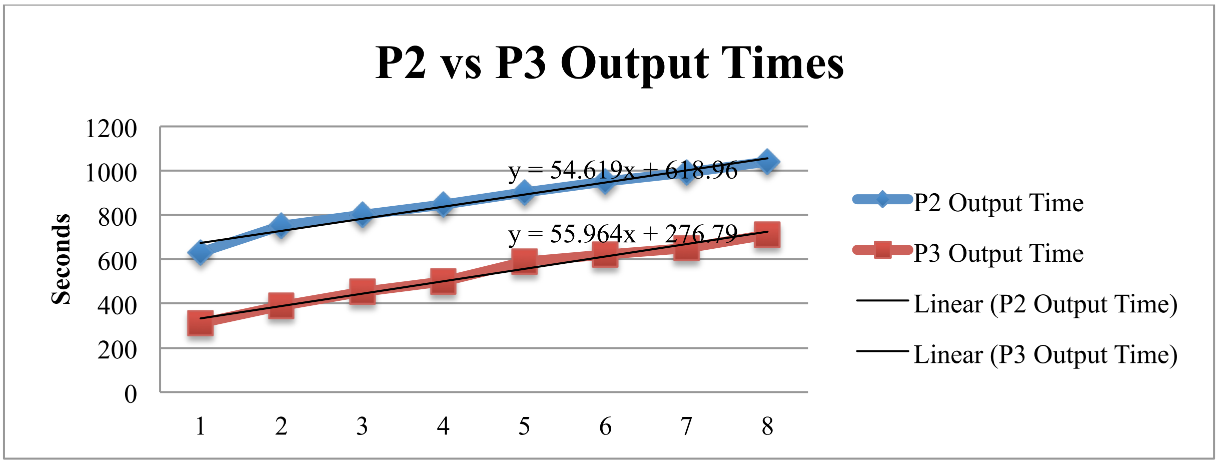


APPENDIX G.2

Output Analysis Graph of Team-2 (Phase-2 and Phase-3)

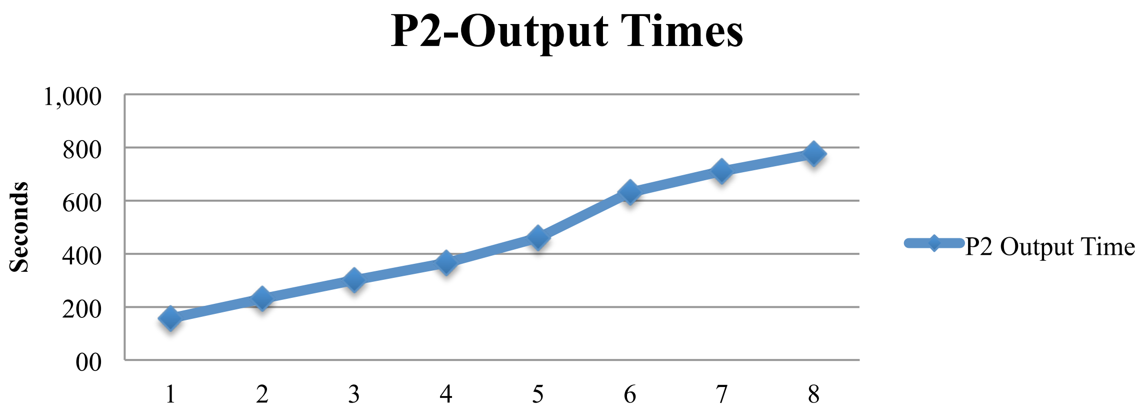


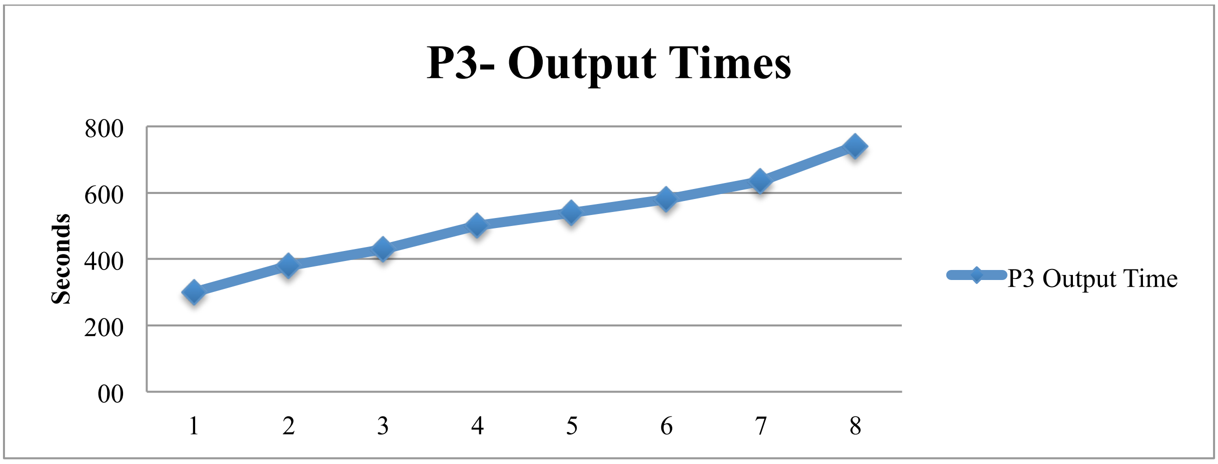


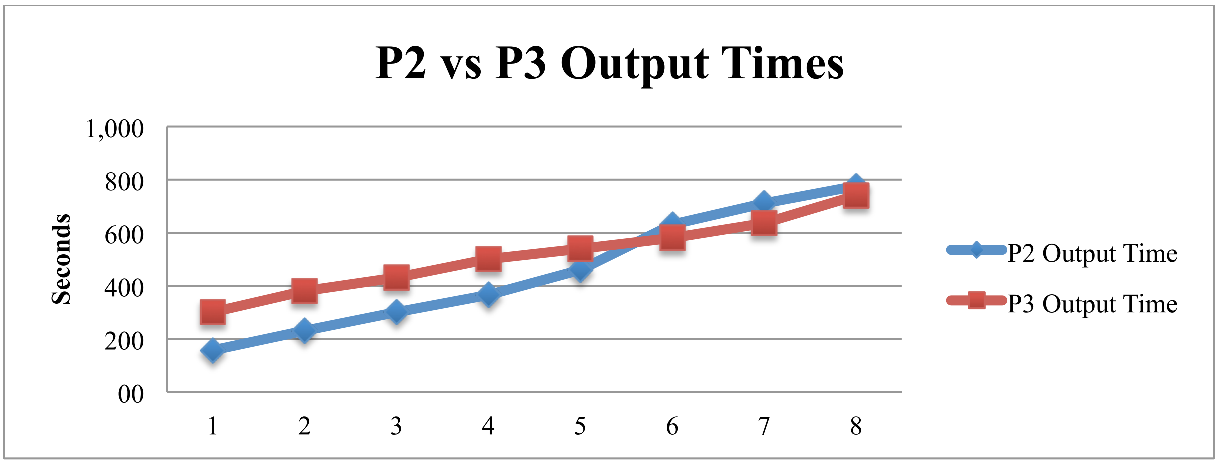


APPENDIX G.3

Output Analysis Graph of Team-3 (Phase-2 and Phase-3)

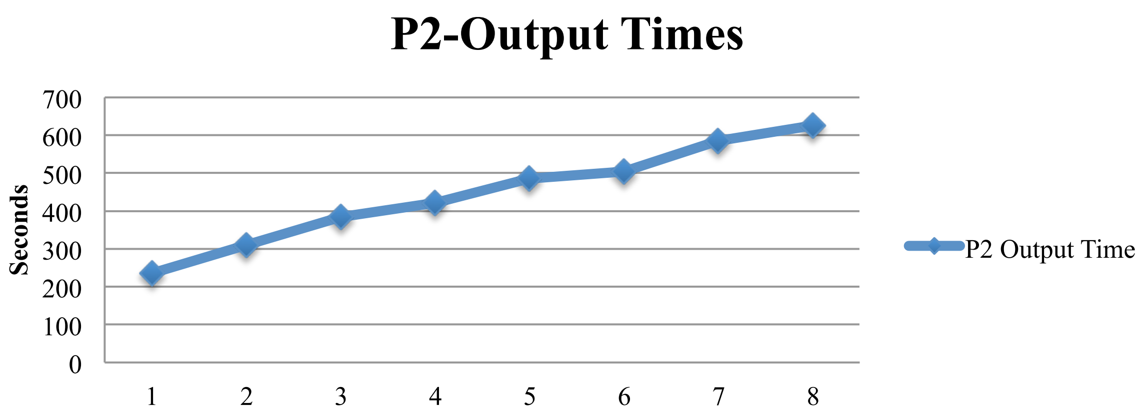


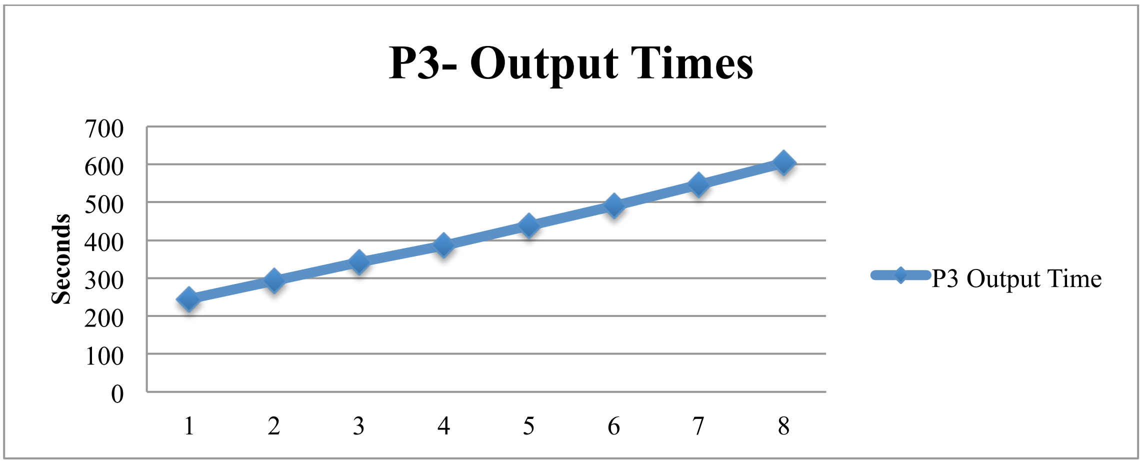


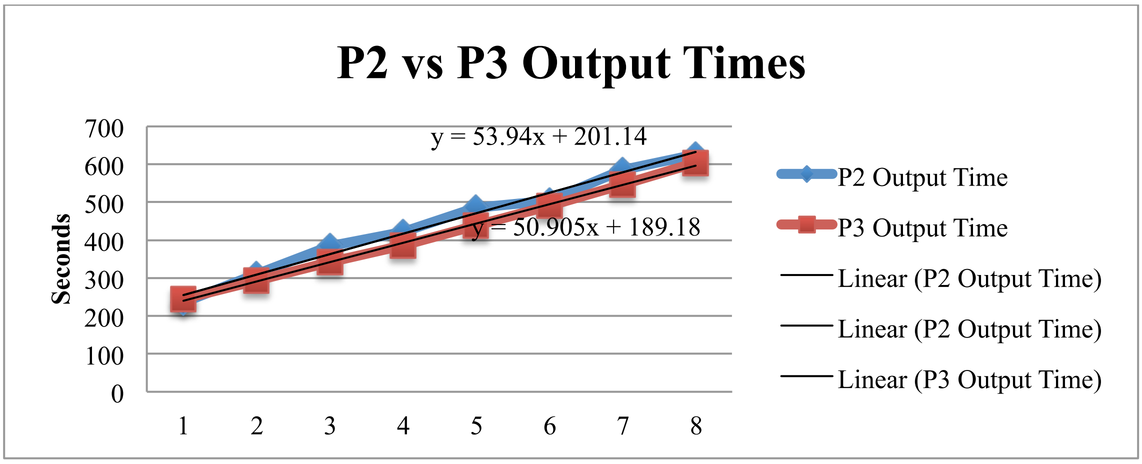


APPENDIX G.4

Output Analysis Graph of Team-4 (Phase-2 and Phase-3)

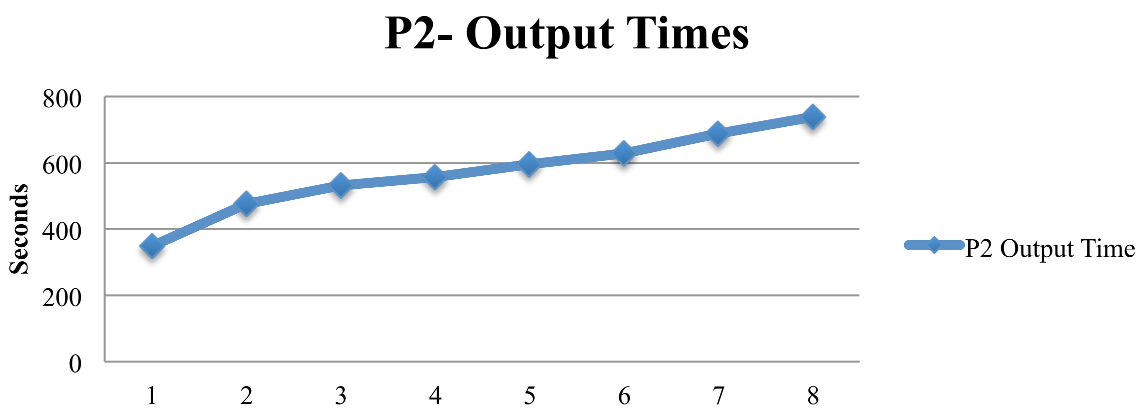


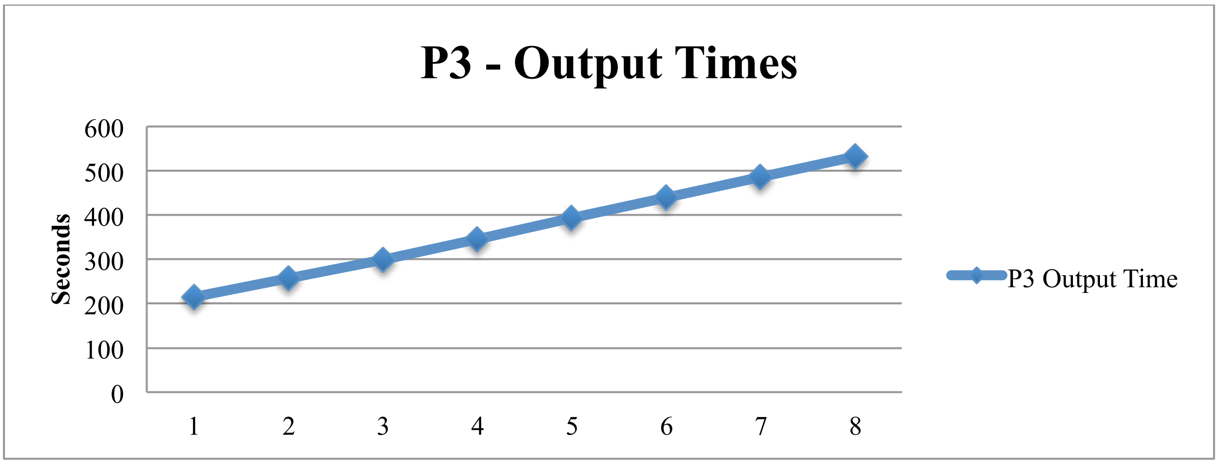


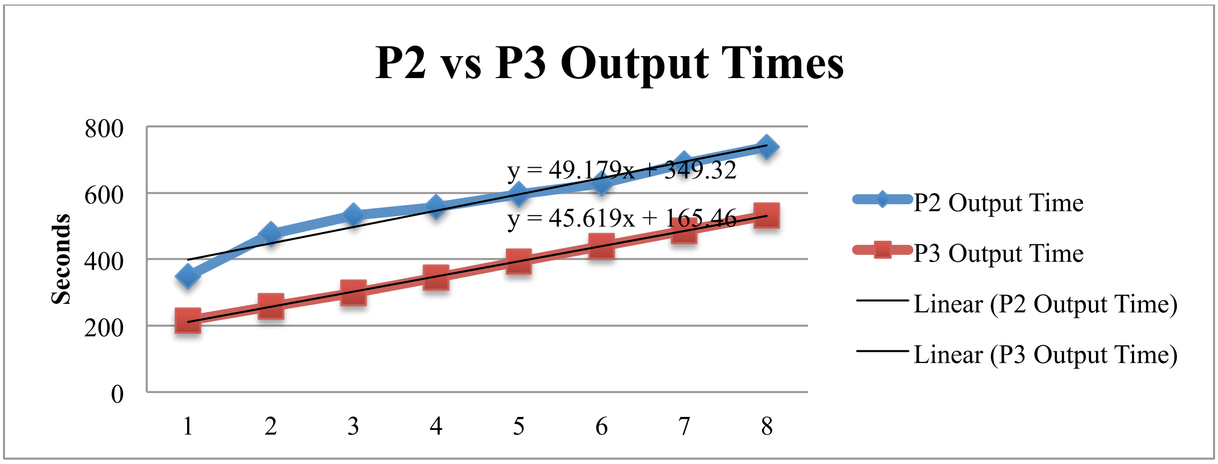


APPENDIX G.5

Output Analysis Graph of Team-5 (Phase-2 and Phase-3)

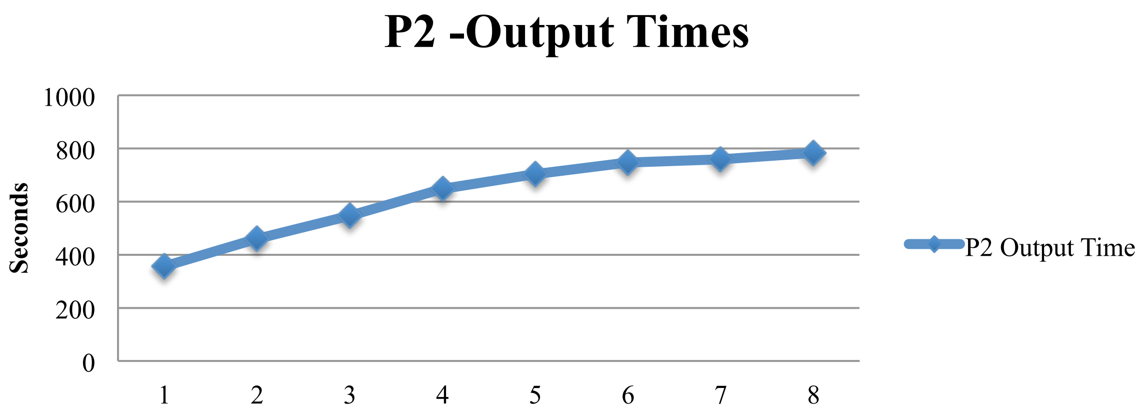


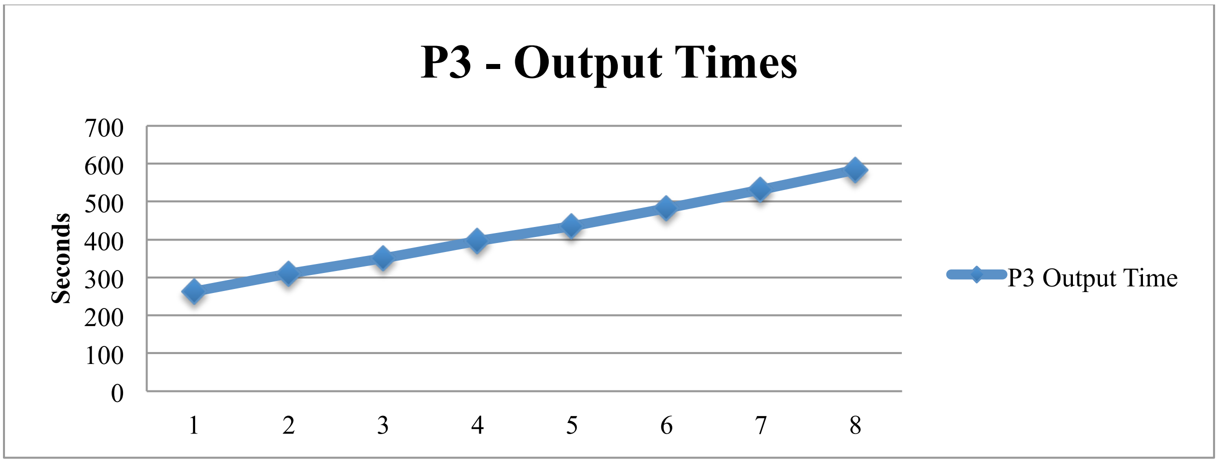


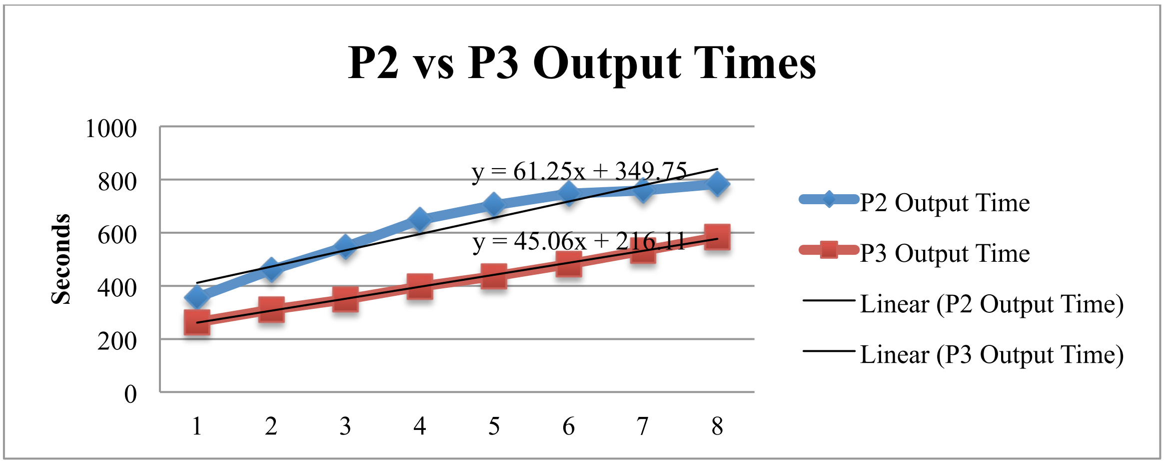


APPENDIX G.6

Output Analysis Graph of Team-6 (Phase-2 and Phase-3)

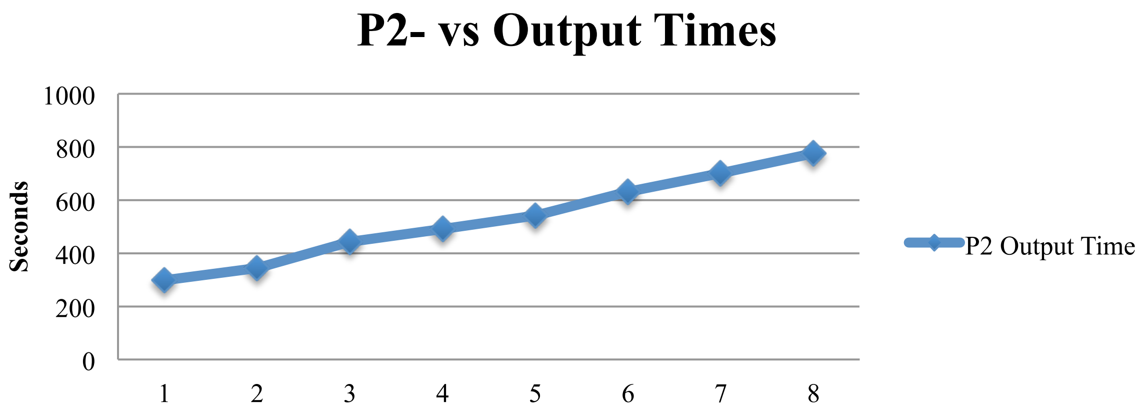


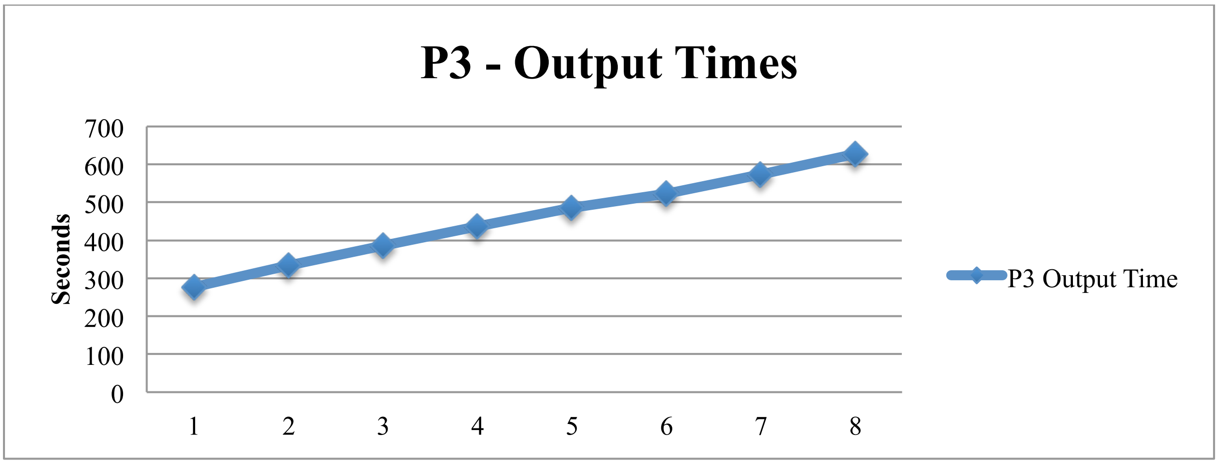


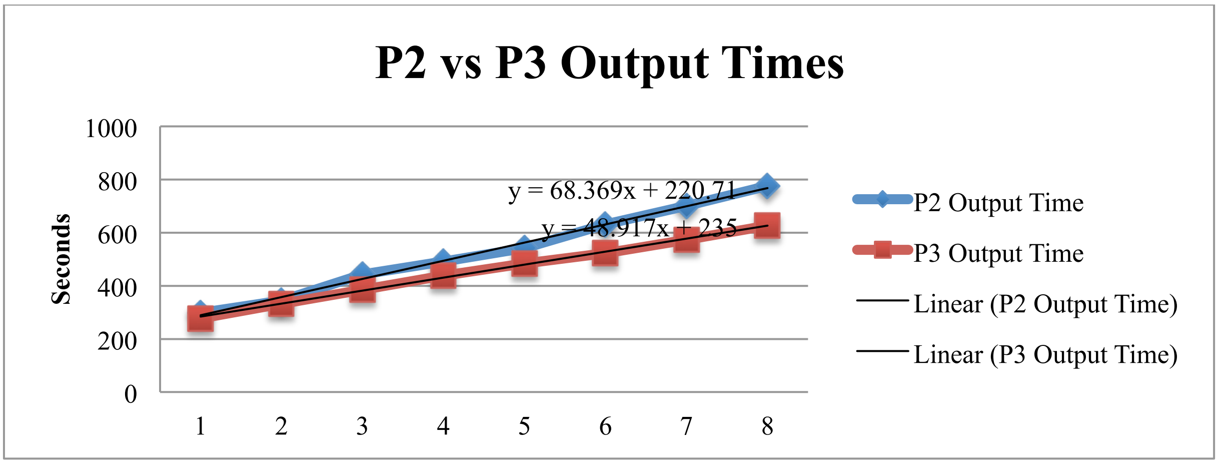


APPENDIX G.7

Output Analysis Graph of Team-7 (Phase-2 and Phase-3)

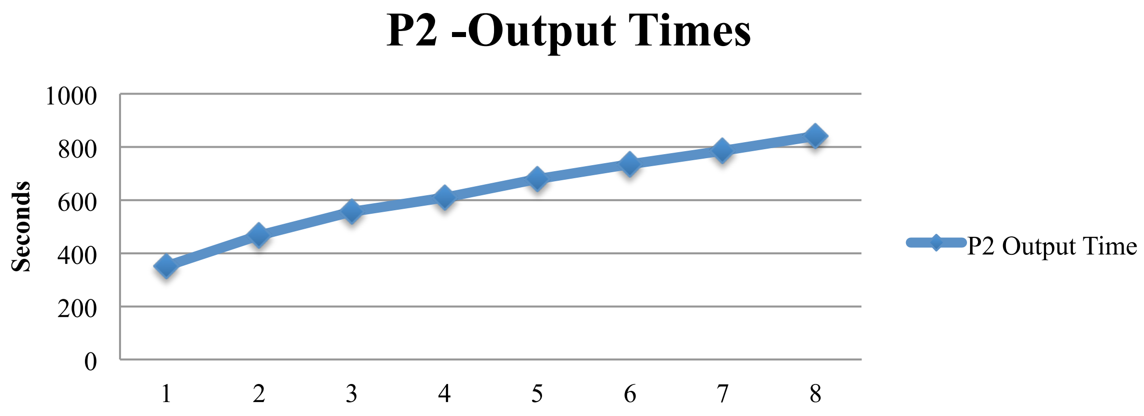


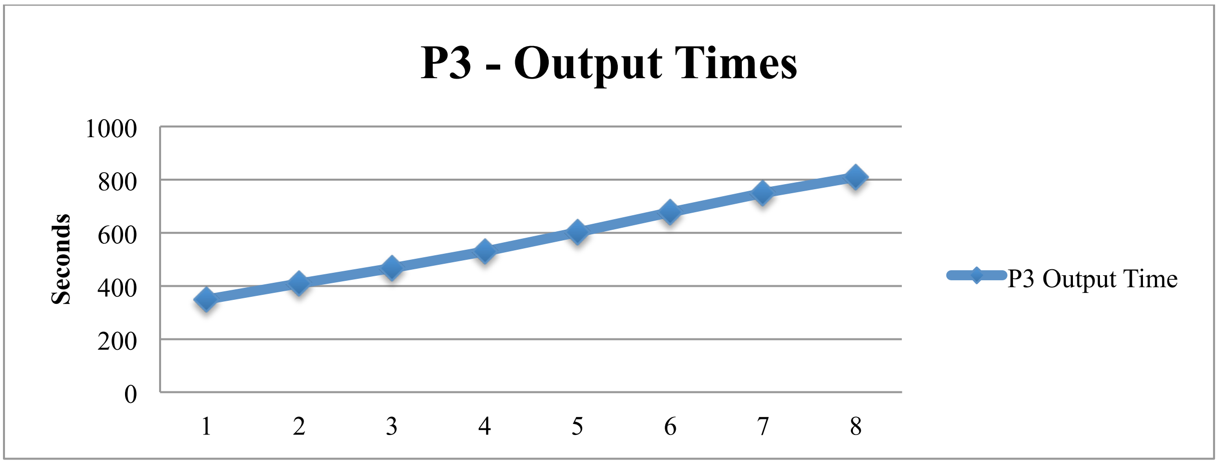


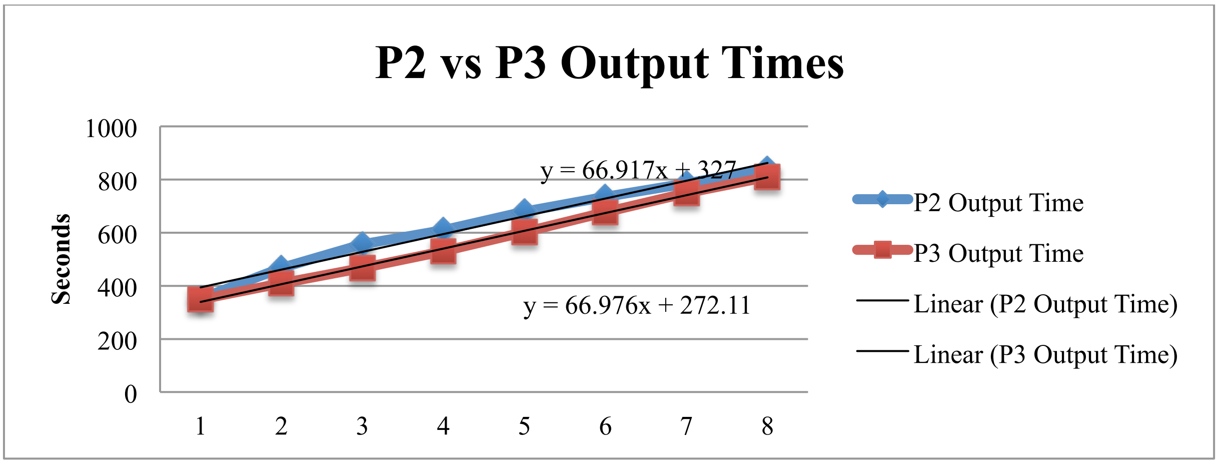


APPENDIX G.8

Output Analysis Graph of Team-8 (Phase-2 and Phase-3)

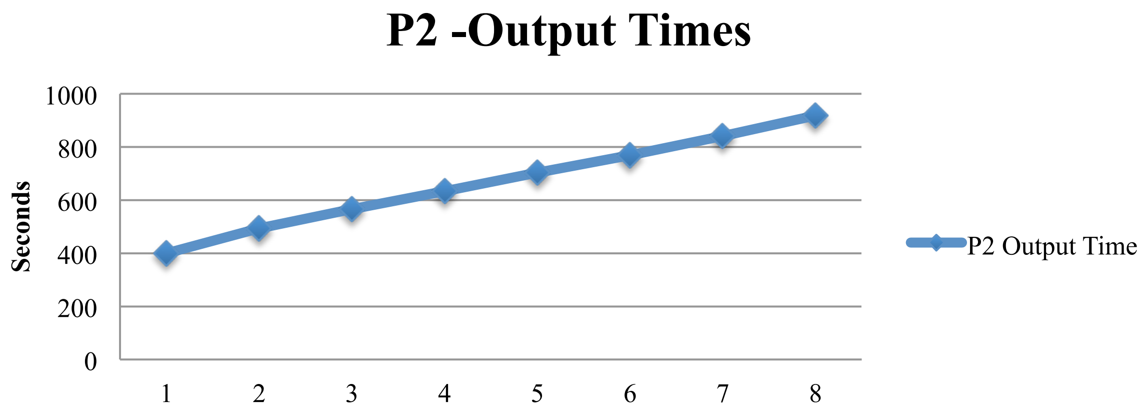


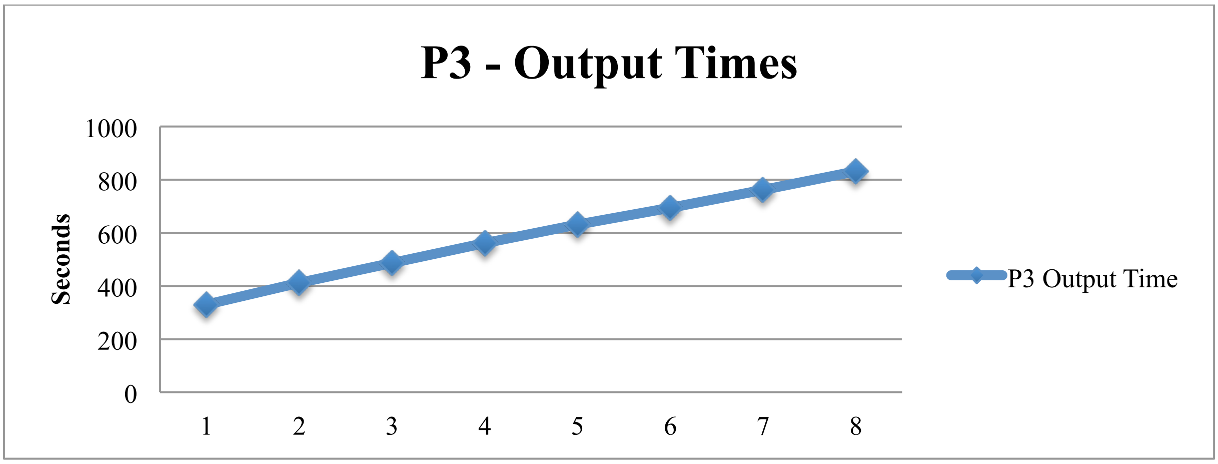


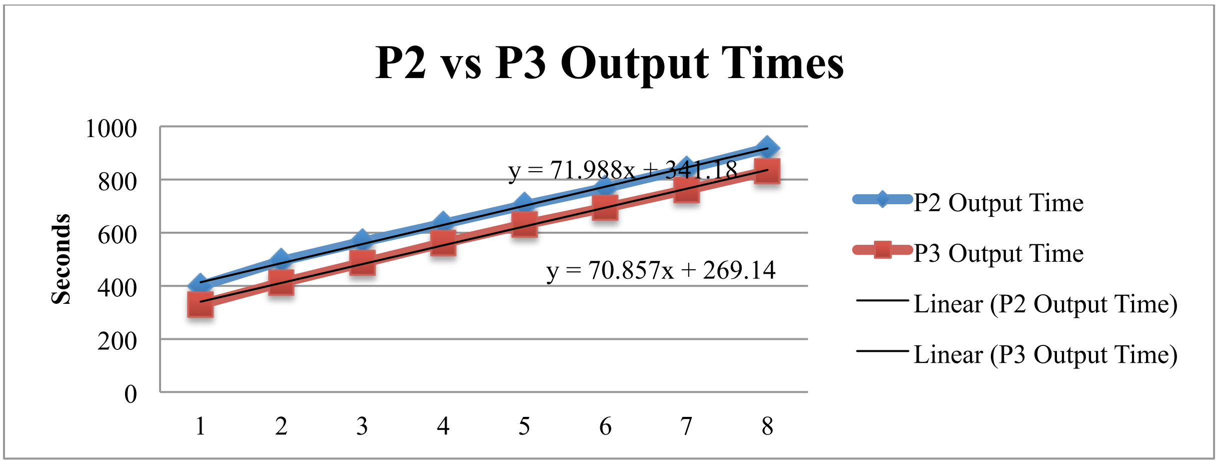


APPENDIX G.9

Output Analysis Graph of Team-9 (Phase-2 and Phase-3)

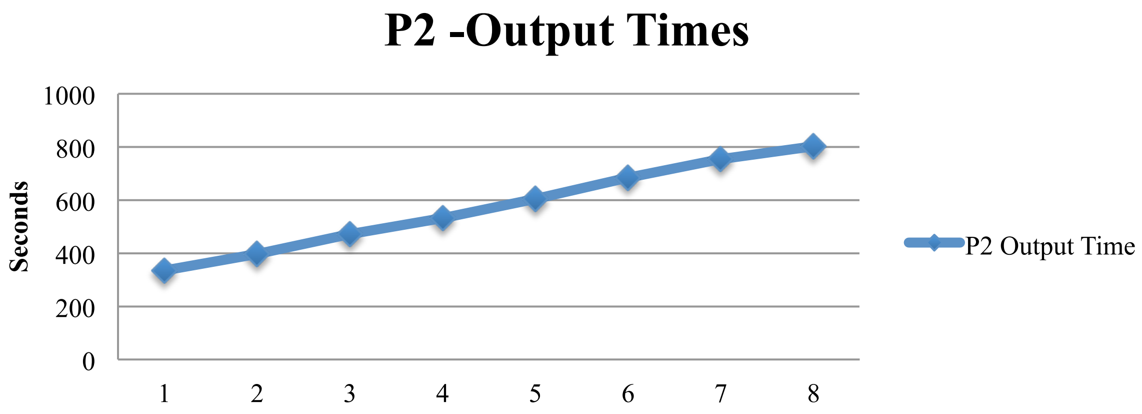


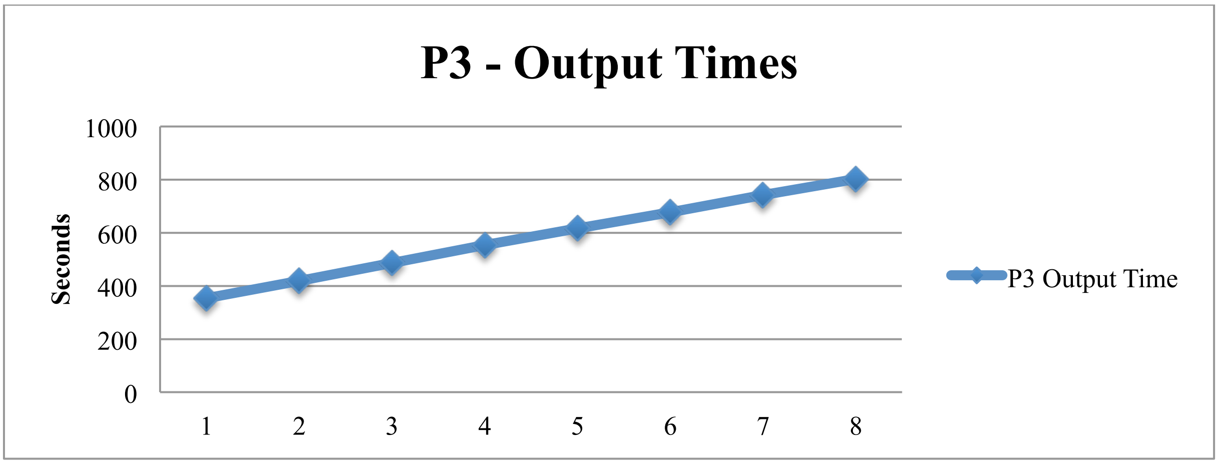


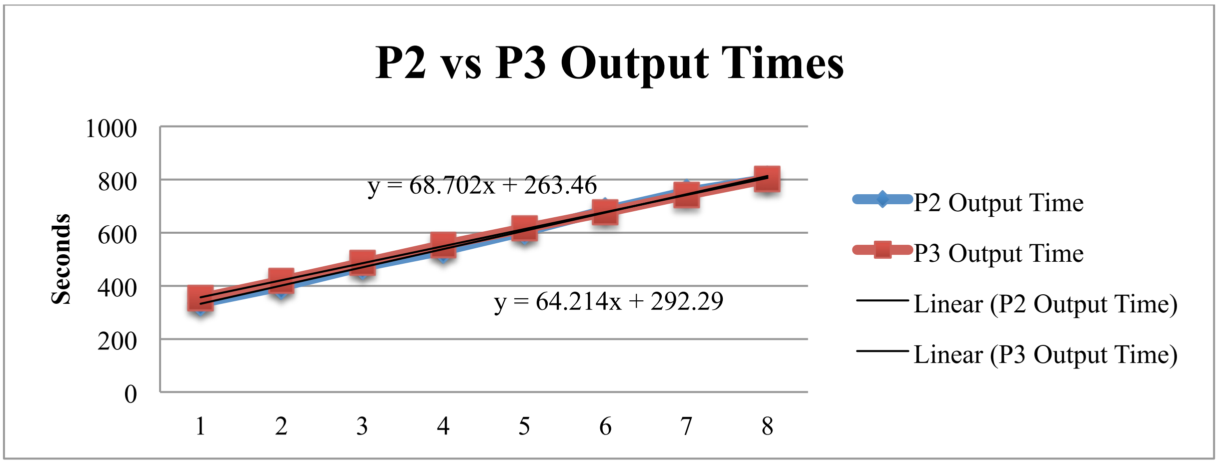


APPENDIX G.10

Output Analysis Graph of Team-10 (Phase-2 and Phase-3)

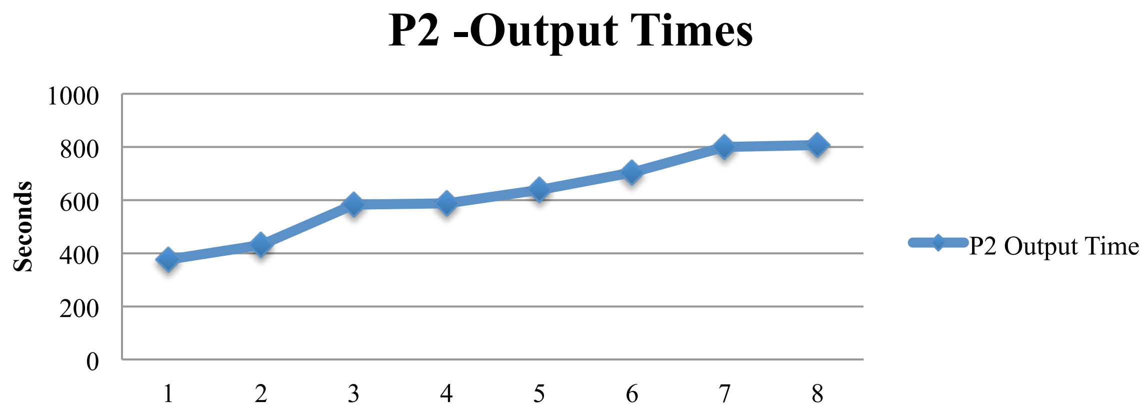


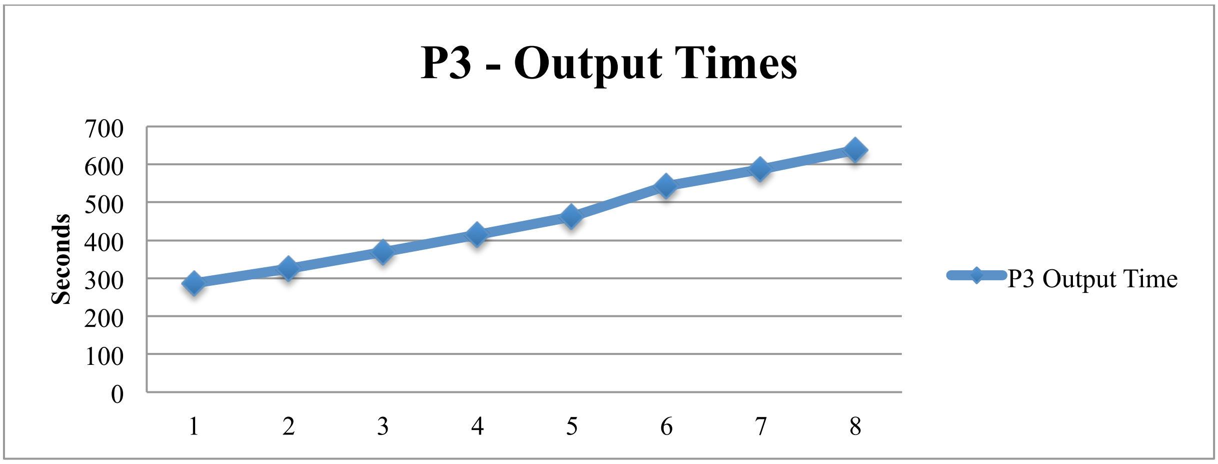


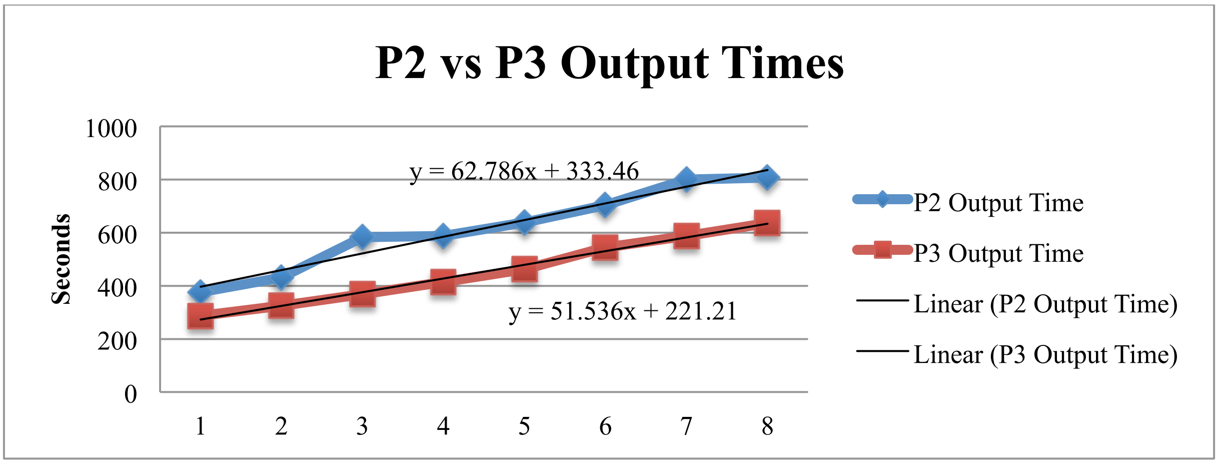


APPENDIX G.11

Output Analysis Graph of Team-11 (Phase-2 and Phase-3)

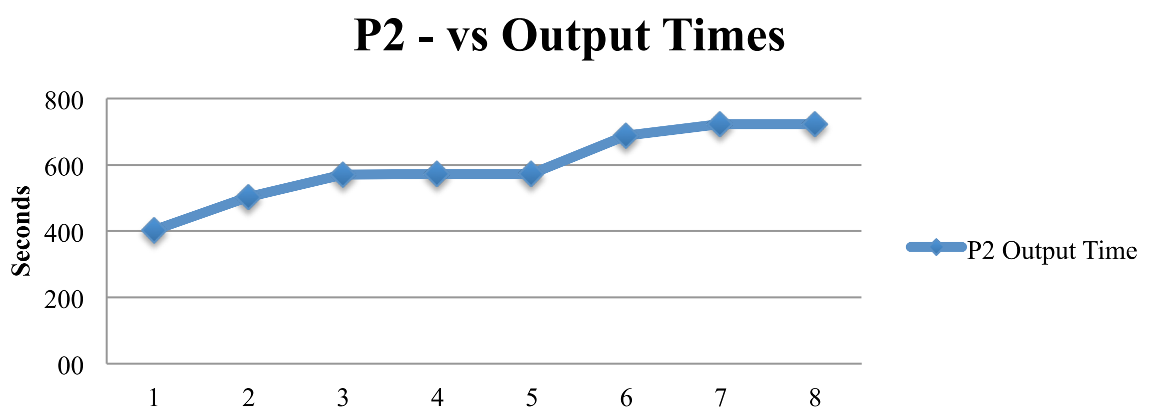


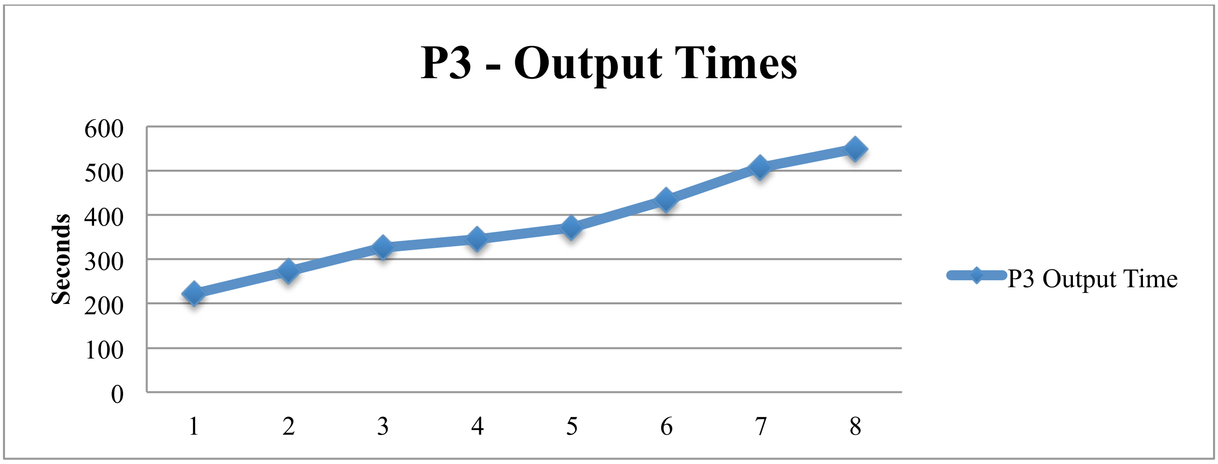


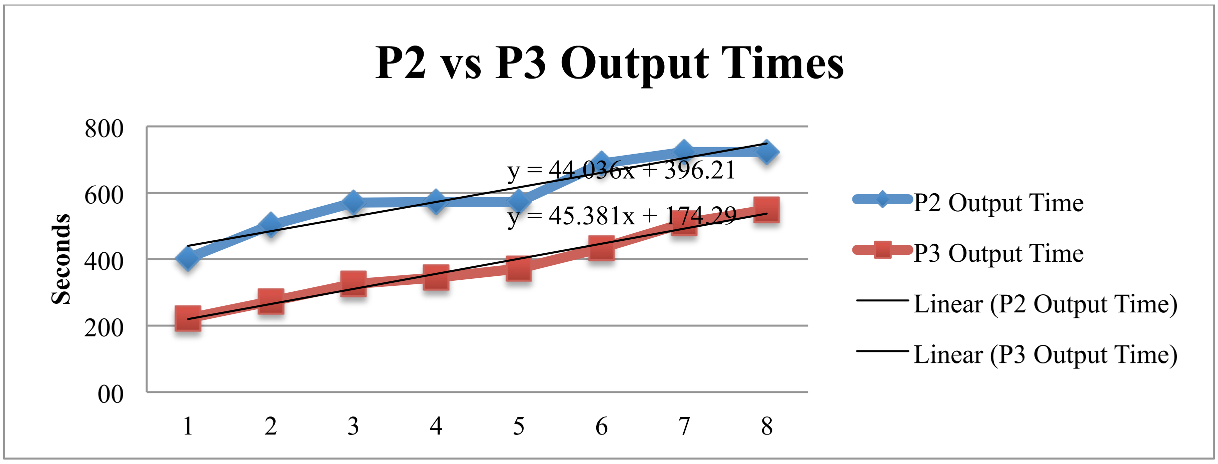


APPENDIX G.12

Output Analysis Graph of Team-12 (Phase-2 and Phase-3)







APPENDIX H.1

Participants Profile Analysis Data – Phase.1

Gender (Male:M; Female:F). Sector (Discrete: D; Process:P). Collar (Blue:B; White:W)

Team No	Gender	Age	Sector	B/W/S	Completion Time (sn)	Defect (1/N)
1	M	29	M	W	490	1
1	M	32	M	B	650	
1	F	33	M	W	657	
1	M	28	M	W	890	1
1	M	29	M	W	923	
1	M	50	M	M	1622	1
2	M	29	M	W	567	
2	M	37	M	W	1123	
2	F	39	C	B	1159	1
2	M	32	M	W	1161	
2	F	48	M	W	1490	
3	M	28	M	W	570	1
3	M	31	M	W	799	
3	M	34	M	W	900	1
3	M	37	C	W	940	1
3	M	38	M	W	1092	1
3	M	40	M	W	1310	1
3	F	51	C	W	1358	1
3	M	45	M	W	1247	
4	F	28	M	W	530	1
4	M	26	C	W	840	
4	M	40	M	W	1120	1
4	F	37	M	W	1250	1
4	M	42	M	W	1273	
4	M	44	M	W	1430	
5	M	28	M	B	590	
5	F	33	M	W	730	
5	M	32	C	W	789	
5	M	30	M	W	856	
5	F	41	M	B	930	1
5	M	37	C	W	1310	
5	M	37	M	W	1390	1
6	M	27	M	W	555	
6	M	29	M	W	662	1
6	M	27	M	B	750	
6	M	29	M	W	930	1
6	M	46	M	B	1130	

6	M	39	M	W	1503	1
7	F	33	M	W	620	
7	M	26	M	B	637	
7	F	33	M	W	850	
7	M	31	C	W	998	1
7	M	33	M	W	1080	1
7	F	41	M	B	1196	1
7	F	39	M	W	1250	1
7	M	39	M	W	1290	1
8	M	26	M	W	594	
8	M	28	M	W	718	
8	F	33	M	W	745	
8	M	29	M	W	862	
8	M	33	M	W	910	
8	M	39	C	W	1320	1
8	M	56	C	B	1438	1
9	M	28	M	B	630	
9	M	28	M	B	750	1
9	M	33	M	W	795	
9	F	28	M	W	935	
9	M	33	M	W	1080	
9	F	42	C	W	1378	
9	F	45	C	B	1520	1
9	M	47	C	B	1560	
10	F	29	M	B	770	
10	M	29	M	W	745	1
10	M	40	M	B	1005	
10	M	33	M	W	1148	
10	M	38	M	W	1460	
10	F	53	M	W	1680	1
11	M	27	M	B	634	
11	M	28	M	W	900	
11	M	31	C	W	1006	1
11	F	28	M	B	1157	
11	M	35	M	W	1200	
11	M	39	C	B	1490	1
11	M	49	C	W	1560	
12	F	29	M	W	720	
12	M	29	M	W	830	1
12	F	45	M	B	1025	1
12	M	32	C	W	1560	1
12	M	50	M	W	1576	1
12	F	49	M	W	1680	1

APPENDIX H.2

Participants Profile Analysis Data – Phase.1

$\bar{X}$ represents mean value of age. $\bar{Y}$ represents mean value of completion times. a represents age number of participant. OT represents output of participant. n represents number of participants

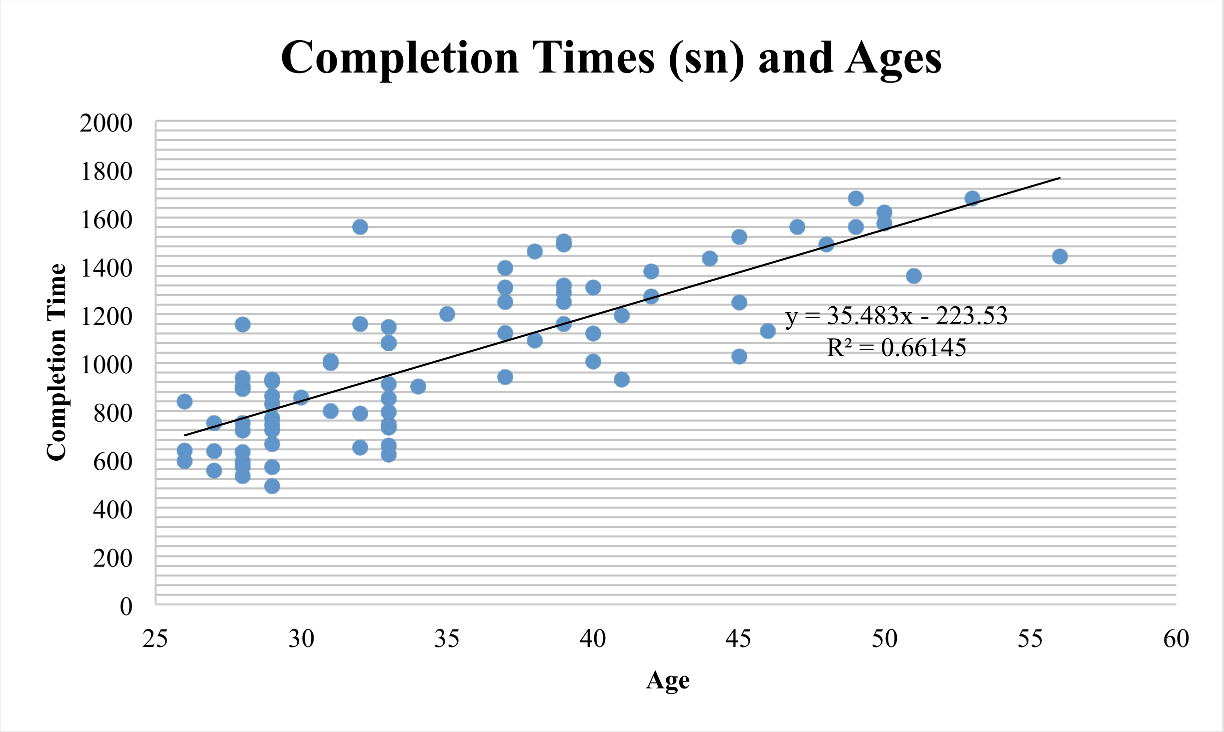
R is calculated as below;

$$r_{x.y} = \frac{\sum X_i Y_i - \frac{\sum X * \sum Y}{n}}{\sqrt{(\sum X_i^2 - \frac{\sum Xi}{n})(\sum Y_i^2 - \frac{\sum Yi}{n})}}$$

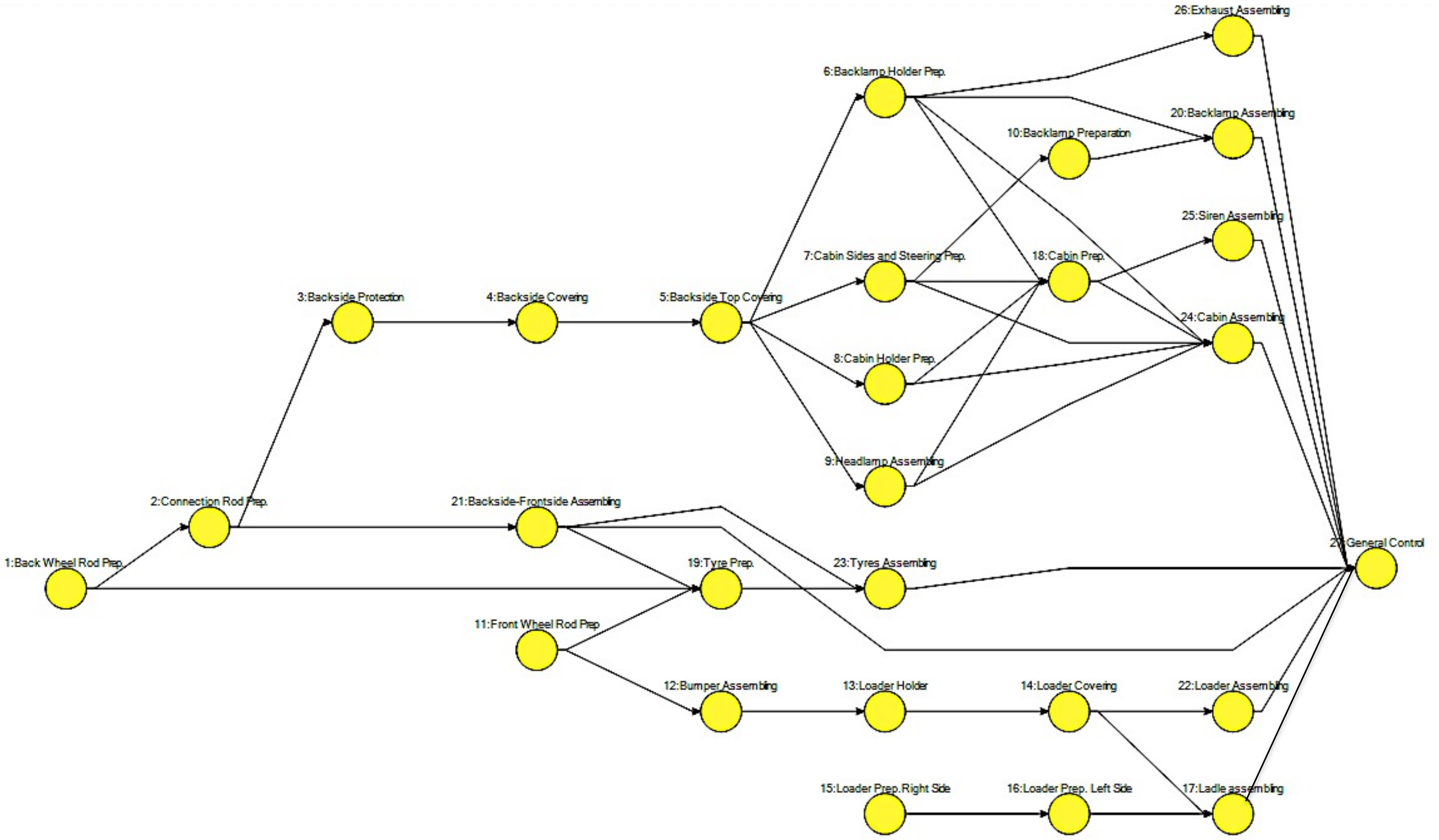
$$r_{x.y} = \frac{3096727 - \frac{2838 * 86818}{80}}{105152 - \frac{2838^2}{80} * 94251176 - \frac{82818^2}{80}}$$

$$r_{x.y} = 0.813$$

$$R^2 = 0.661$$



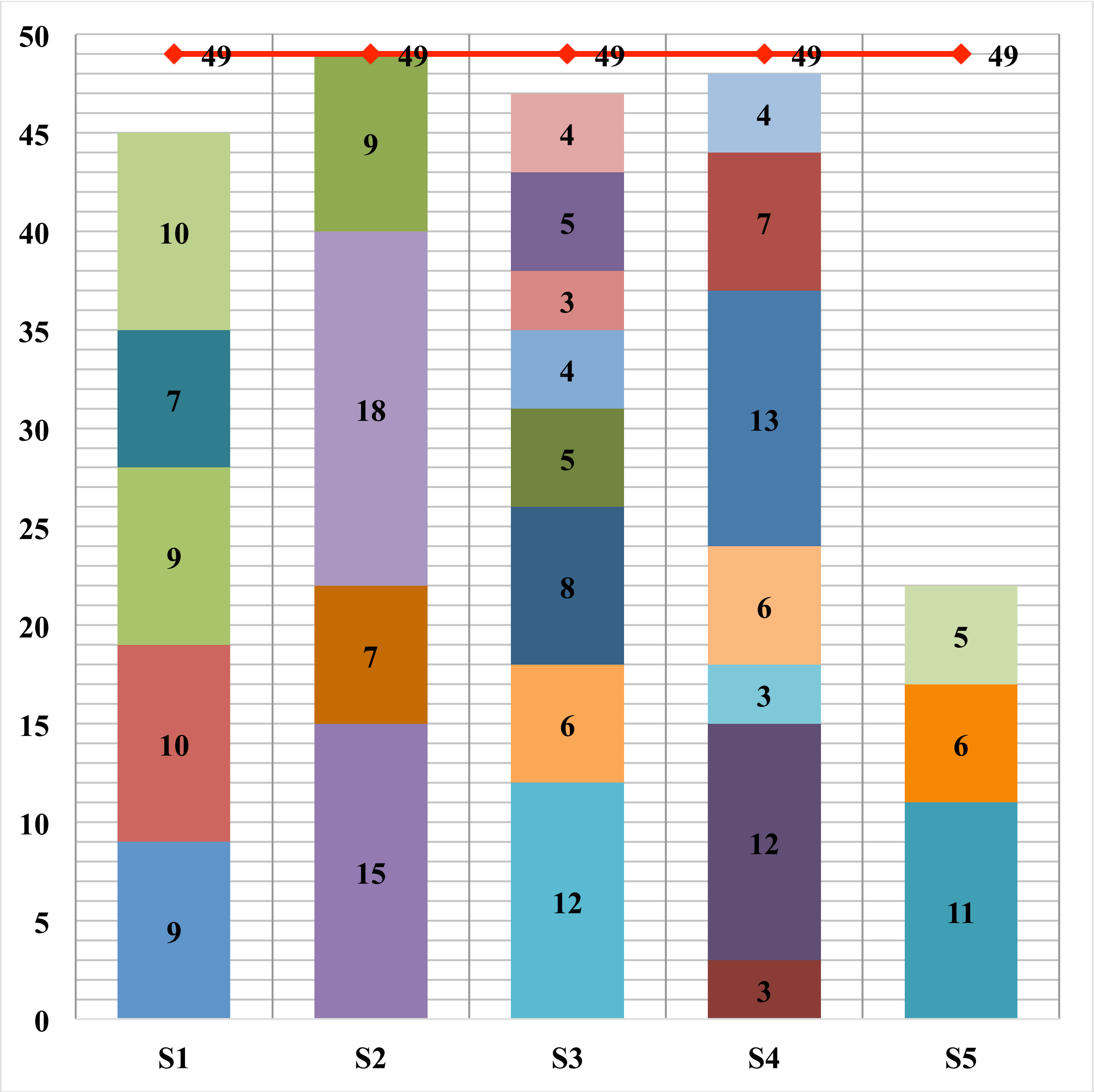
APPENDIX I Precedence Diagram of 7630



APPENDIX J.1

Task Assignment by ProPlanner®

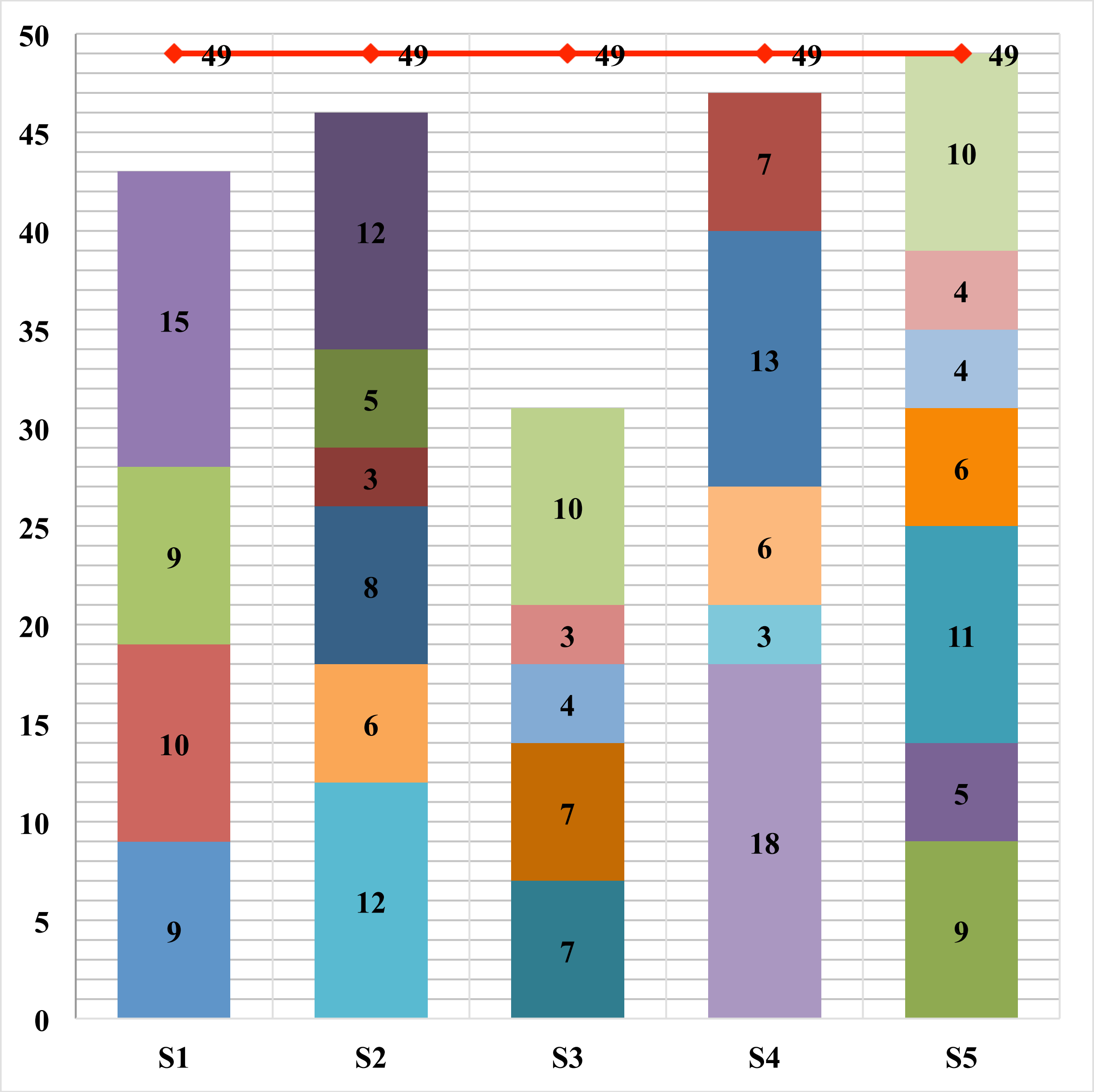
	Station-1	Station-2	Station-3	Station-4	Station-5
TASK ELEMENTS	11	16	13	10	23
	1	12	5	17	24
	15	4	9	20	27
	2	21	14	19	
	3		6	8	
			22	18	
			7	25	
			26		



APPENDIX J.2

Task Assignment by Based on Instructional Manual

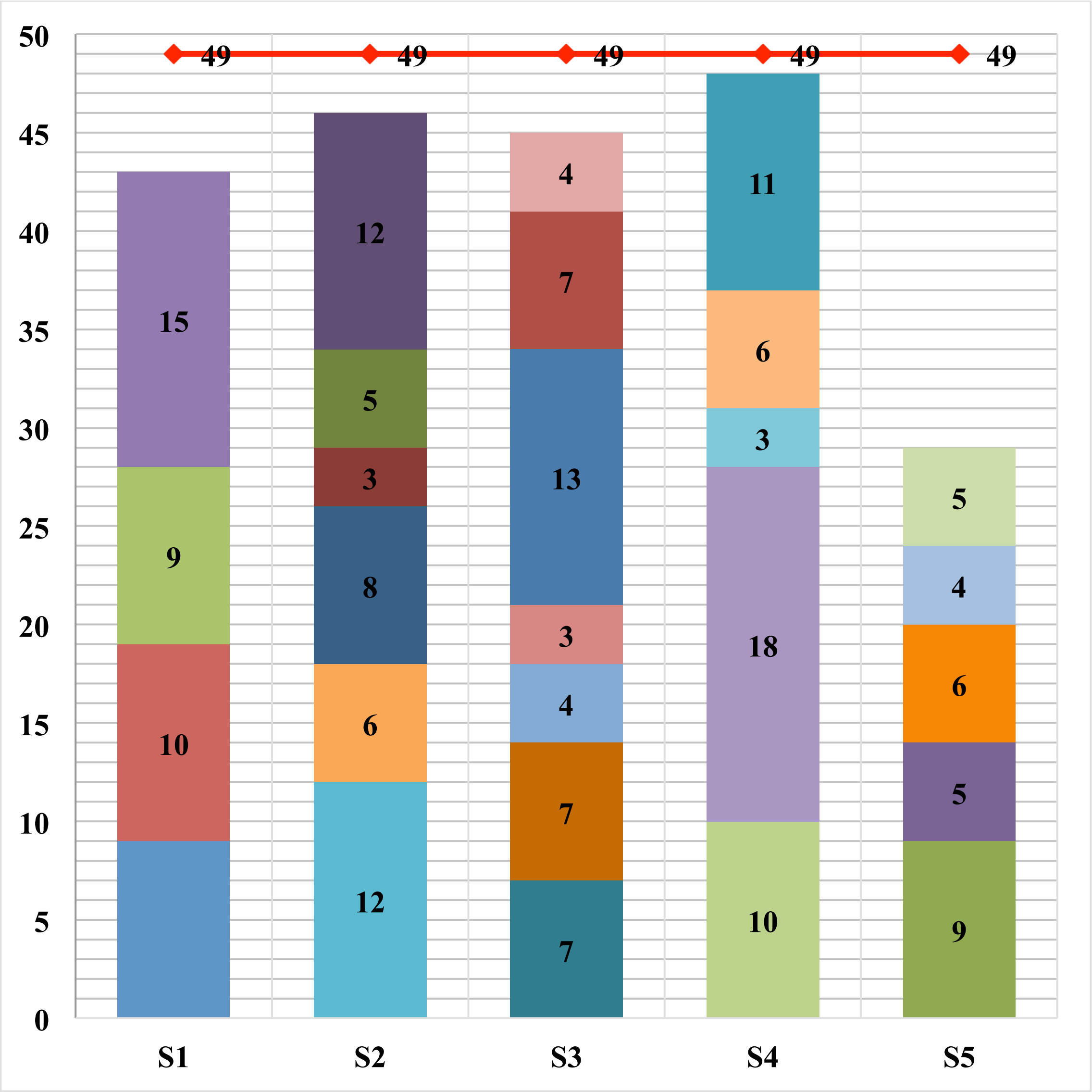
	Station-1	Station-2	Station-3	Station-4	Station-5
TASK ELEMENTS	1	5	11	16	21
	2	6	12	17	22
	3	7	13	18	23
	4	8	14	19	24
		9	15	20	25
		10	16		26
					27



APPENDIX J.3

Task Assignment by Assign Jobs Manually

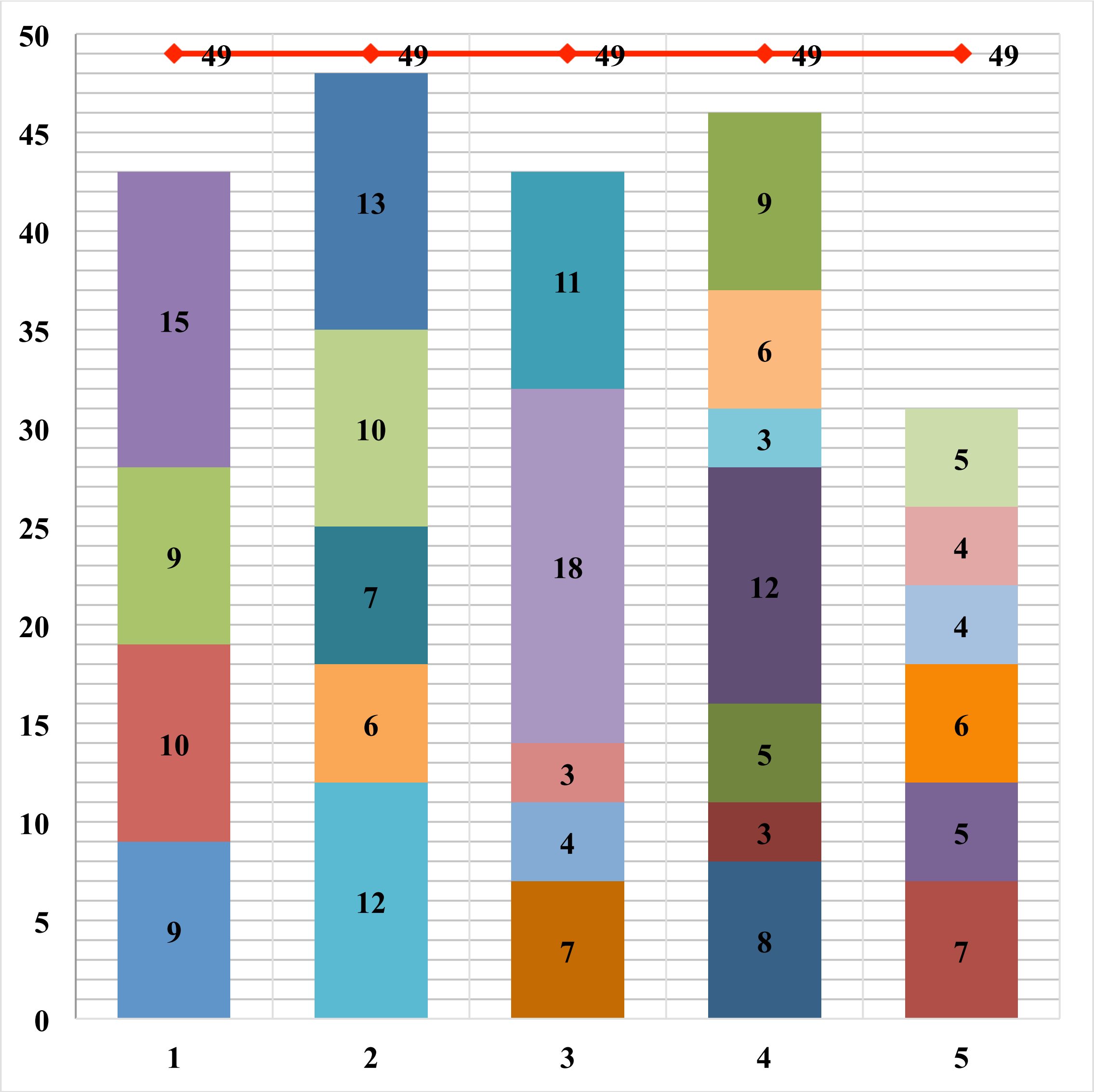
	Station-1	Station-2	Station-3	Station-4	Station-5
TASK ELEMENTS	1	5	11	15	21
	2	6	12	16	22
	3	7	13	17	24
	4	8	14	18	25
		9	19	23	27
		10	20		



APPENDIX J.4

Task Assignment by Improperly Used SALBP-1 Alghorithm

	Station-1	Station-2	Station-3	Station-4	Station-5
TASK ELEMENTS	1	5	12	7	20
	2	6	13	8	22
	3	11	14	9	24
	4	15	16	10	25
		19	23	17	26
				18	27



BIOGRAPHICAL SKETCH

The writer was born in 1987 in Eskisehir, Turkey has finished high school education in Kılıçoğlu Anatolian High School in 2005. He completed his B.Sc on Mechanical Engineering in the Mechanical Engineering Department of Istanbul Technical University in year 2009. He also completed Undergraduate Development Program of Toyota Turkey. His research interest and focus are in the areas of Lean Production and Lean Management Systems. Writer is working as Lean Consultant for Lean Institute Turkey since 2010. He is the concept creator of Yamazumi Games and experiential learning trainings and admin of yalindanisman.com website.

PUBLICATIONS

Yukselen, C., Ahiska, S.S., King, R.E. (2014). An educational game for assembly line design using lean concepts. Proceedings of the 2014 Industrial and Systems Engineering Research Conference, May 31 - June 3, Montreal, Canada (in press).