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CONTENTS

Operational Research in Engineering Sciences: Theory and Applications
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QUALITY IMPROVEMENT OF THE E-COMMERCE WEBSITE USING INTEGRATION OF KANO MODEL-IPA WITH QFD APPROACH

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Research paper

Abstract: *This study was conducted to analyze the quality of e-commerce websites, find out which items need improvement, and make improvement design e-commerce websites. This study uses the kano model and Importance Performance Analysis approach based on 7 dimensions with 39 attributes. This study used the survey results from 103 respondents who regularly use the e-commerce website Tokopedia.com. The results of the questionnaire through the validity and reliability tests were used to analyze the reliability of items and the feasibility of the results of the questionnaire. After that, the results of the questionnaire through the corellation and hypothesis tests were used to know the relationship between variables. The findings show that 7 attributes influence customer satisfaction. However, the findings are still nowhere near the expectations. Thus, it requires being the focus of improvement. Improvements in design of 7 attributes in the form of House of Quality with 6 technical features needed to improve the quality of e-commerce website Tokopedia.com. Therefore, effective management strategies can be applied to overcome the intense competition in the e-commerce industry.*

Key words: *Website quality, Kano model, Importance Performance Analysis, E-commerce, QFD, Customer satisfaction*

1. Introduction

Technology has rapidly developed along with the times, which allows people to be able to work more easily and effectively (Wilson & Keni, 2018). One of the examples is the increase in internet development. The internet is a global network system that allows people to communicate globally, get information easily, as well as buy and sell products and services online. The internet has a big influence on how people work, shop, make payments, travel, and socializes (Kaur, 2011). The development of the internet in recent years has changed the way people do business for they are starting to do it in a digital manner rather than the traditional way.

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Technological advances and developments make life easier for human beings by making online business as well as buying and selling a trend in the future. In traditional trade, the seller and buyer have to meet each other in the same place, negotiate, and conduct transactions, which require both parties to agree on the prices. Meanwhile, in e-commerce or online trading, there is no need for buyers and sellers to meet each other. Instead, they meet through a website that acts as an intermediary that connects the two parties and facilitates the transaction. Therefore, buyers can buy products or services from sellers, while sellers can do business even if they do not have a place or shop (Wilson et al. 2019). E-commerce can be defined as a commercial transaction between two parties, organizations, and individuals which is carried out through a network or website (Psaila & Wagner, 2007). E-commerce covers several types of activities, such as retail shopping, banking, ordering food, ticketing, and others. Most people use the website as e-mail, looking for information, social media, and a place for online transactions. This makes buying and selling things online a trend in the future. Buying and selling online in the e-commerce industry is defined as the efforts made to market a product or service as well as to rebuild relationships between sellers and buyers through internet media (Kotler & Amstrong, 2014). Hence, a website quality assessment is needed based on several criteria and items to describe things expected of a website (Rondovic et al, 2017). Website quality can affect repurchase intentions. On e-commerce sites, repurchase intentions have been underlined by several researchers or actors (Wilson et al. 2019; Wilson & Keni 2018; Wilson 2018; Wilson & Christella 2019). In this case, the quality of website appearance is known as a factor that can build repurchase intentions to consumers. It is an advantage for the company when a consumer or customer has the intention to rebuy things from the same e-commerce company. There is a possibility that customers will buy products or services from other companies in the same industry. Moreover, some researchers have underlined that the relationship between customer loyalty and the success of e-commerce companies is the key to achieving success in the e-commerce industry since it can indirectly retain customers (Lee et al, 2009).

One of the important things in repurchase in e-commerce is the website user interface features that are well designed that enable a positive impression on customers who will do a repurchase (Fan & Tsai, 2010). The quality of the website's appearance has a considerable effect in influencing customer trust to shop on the site (Gregg & Walczak 2010). The quality of website design is related to the customer's initial online buying behavior (Zhou et al., 2009). Online shopping websites are very important for businesses, retailers, and consumers where the features on the website are designed innovatively. For that reason, the e-commerce industry has to develop high-quality websites that provide a better online experience to attract and retain their customers in e-commerce (Stuart, 2003). The main challenges for e-commerce organizations are understanding the users' needs and developing them. E-commerce companies with websites that are difficult to use will protect a bad image on the Internet and weaken the company's position in the e-commerce business (Barnes & Vidgen, 2002). This study aims to find out the extent of the satisfaction level of Tokopedia.com e-commerce web users through measurement between the current level of quality (perception) and the desired quality (expectations). The next goal is to be able to describe the position of the Tokopedia.com e-commerce website quality items to enable seeing which items are by the user's expectations and which ones need improvement. Therefore, it can be designed to propose improvements on the

Tokopedia.com e-commerce website. This study differs from previous studies. Previous studies only reached the stage of e-commerce website quality analysis, while this study proposed improvements on the results of e-commerce website quality analysis based on kano model and importance performance analysis methods using improvement scales Quality Function Deployment (QFD). Kang et al (2016) studied the evaluation of e-commerce websites based on the E-S-Qual method. A study conducted by Ilbahar and Cebi (2017) analyzed and classified design parameters according to customer expectations for evaluating the usefulness of e-commerce websites. Mohd and Zaaba (2019) argue on usability and security factor analysis on e-commerce websites.

2. Literature Review

In general, quality is a characteristic of a product or service that reflects how well the product or service meets customer satisfaction (Negash et al. 2003). According to a study, customer perceptions on the quality of a website are based on features on the website that meet customer needs and impress the total excellence of the website. The previous researchers also mentioned that various dimensions of website quality which can be categorized as security, information quality, ease of use, and service quality. Customer perceptions of the quality of the website are based on features on the website that meet the needs and impressions of customers towards the website (Mona et al., 2013). Attractive website designs on e-commerce websites motivate consumers to engage in online shopping (Ganesh et al., 2010). According to some researchers, the features on the website have an important influence on online purchase intentions (Mansori et al., 2012). Another study argues that informative websites allow customers to compare and evaluate product alternatives thereby increasing customer satisfaction and thus influencing online purchase intentions (Hausman & Siekpe, 2009). The quality of information offered by a brand on online shopping sites is also an important factor. A specific study revealed that information quality has the highest influence on customer satisfaction among all dimensions of website quality (Kim & Jones, 2009).

2.1. Kano Model

Kano model is used to determine how effective an indicator plays a role in improving service quality. The Kano's attributes are divided into several categories. The first category is Must be (M) or basic needs, the customer simply accepts when it is fulfilled. However, if the product or service fails to satisfy the customer's basic needs, the customer will be very dissatisfied. For instance, although having unfriendly waiters causes customer dissatisfaction, having friendly service does not increase customer satisfaction since having a friendly waiters is a basic need (Garibay et al, 2010). The second category is One dimensional (O) or performance needs. The level of customer satisfaction is related to one-dimensional performance; thus, the higher the perceived service quality, the higher the customer satisfaction, and vice versa. When attributes are fulfilled, customers are satisfied; if they are not fulfilled, customers are dissatisfied. The level of customer satisfaction increases in accordance with the level of such attributes. Therefore, the categories of must be and one dimensional are conditions needed to achieve customer satisfaction (Basfirinci et al, 2015). The third category is Attractive (A) or excitement needs, which shows a high level of customer satisfaction when fulfilled, but does not cause dissatisfaction when it is not fulfilled because it is not expected by the customer who may not know the product features. The fourth category is Reserve (R), which indicates that if an indicator in this category exists, the customer is dissatisfied, while if the opposite is true, the customer is highly satisfied. The fifth category is Indifferent (I), which indicates that the existence of indicators in this category seems to have no impact on customer satisfaction. The sixth category is Questionable (Q), which involves indicators that are still questionable since the possibility of customers being satisfied or dissatisfied is unclear (Dewi et al, 2018). The next step is determining the Kano's category for each indicator. If (M + O + A)> (I + R), then the Kano's category for the x-indicator is max {M, O, A), otherwise (M + O + A) <(I + R) then the Kano's category for the x-indicator is max {I, R} (Kuo et al, 2012). The researcher will then use Importance Performance Analysis to process the attributes that fall into the M, O, and A categories.

2.2. Importance Performance Analysis (IPA)

Importance Performance Analysis (IPA) has been one of the most extensively acknowledged systematic methods for measuring which items demand improvement. The research focused on the Importance Performance Analysis (IPA), Evans and Chon (1989) examined the capability of the IPA to control tourism strategies in two different places in the US. The investigation showed that local business workers were not content with the company's performance. The next researcher used IPA to compare business competitiveness in Hong Kong with its main competitors in the Asia Pacific region. In analyzing the data, they used IPA for it can provide a basis for their business development strategies (Enright & Newton, 2004). Sorensson's (2013) research results comparing national and international tourists using IPA revealed that national tourists place a higher level of importance on sustainable tourism than international tourists. Meanwhile, there are significant differences between national and international tourists in subsequent tourism. The results from the IPA consist of four quadrants. Quadrant I included the high importance but low performance. The items included in this quadrant represent the main items that need to be improved with top priority. Quadrant II involved high importance with a high level of performance. Thus, it does not need enhancement and the items recorded on this quadrant are meet expectations. Quadrant III is of low importance with low performance as well labeled as a low priority. Therefore, the items included in this quadrant are unimportant and do not pose a threat to the company. Quadrant IV means low importance with a high level of performance. Quadrant IV is labeled as possibly excessive. This shows items that are too much emphasized by the organization. Hence, organizations have to minimize these items. However, rather than focus in this quadrant, companies are obliged to allocate more resources to focus on items that are in quadrant I (Wong et al., 2011).

2.3. Quality Function Deployment (QFD)

Quality Function Deployment is a way to make the needs and desires of customers as part of the design and production of a product or service. QFD is used by companies to identify customer needs in technical languages (Goetsch & Davis, 2014). QFD originated from Japan in 1972. It has been successful as a tool to help systematic quality improvement teams translate market research and customer needs into technical characteristics to satisfy customer desires. In QFD, customer needs are reflected in the planning matrix or so-called 'quality home' or HOQ (Cohen, 1995).

3. Methodology

This study is a survey study that used a quantitative approach by involving samples directly from the existing population. The purpose of this study was to determine the extent of user satisfaction on the quality of e-commerce Tokopedia.com websites, items that need to be improved and also suggestions for improvements on the quality of Tokopedia.com e-commerce websites. Variables measured to determine the quality of the website was to use seven dimensions including Website Design (WD), Product Quality (PQ), Security Quality (SQ), Delivery Quality (DQ), Delivery Accuracy (DA), Customer Service (CS), Customer Perception and Satisfaction (PS). Each dimension consisted of several question items as the basis for compiling the questionnaire. The sampling technique used in this study was simple random sampling where sampling was done randomly from the existing population. In general, based on the theory that sampling for factor analysis requires a minimum of 100 respondents (Kline, 1994). Thus, this study used a 90% confidence level with a 10% error margin where the sample size was 103 respondents. The e-commerce website used as a sample of this study was the Tokopedia.com e-commerce website. The data collection technique used was a questionnaire with a Likert scale and Kano scale. Likert scale consisting of 5 points, from strongly disagree (score 1) to strongly agree (score 5). Kano scale consisting of 5 points, that is M (Must be), O (One dimensional), A (Atractive), I (Indifferent), R (Reserve) dan Q (Questionable).

After the questionnaire was distributed, validity and reliability tests were performed to determine whether the results of the questionnaire were suitable for analysis. An item that had a positive correlation with criteria (total score) and a high correlation showed that the item had high validity as well. Based on this, if the calculated r count value was smaller than the r table value, then then the question item became unvalid. Moreover, it was said to be valid if the calculated value was greater than the r table value. After testing the validity of the questions used in the study, the reliability test was then performed. The reliability test was carried out to find out whether the data collection tool showed the level of accuracy, stability or consistency. Thus, the data can be used for further analysis. An item is considered to be reliable if the value of Cronbach Alpha is bigger than the critical value. The specified critical value is 0.6. If the Alpha value is greater than 0.6 then it is reliable and if the Alpha value is less than 0.6 then it is not reliable (Sugiyono, 2016). After that, the results of the questionnaire through the corellation and hypothesis tests were used to know the relationship between variables. After the correlation and hypothesis testing, the data can be processed using the Kano model and also the importance performance analysis for further analysis. Variabel and attribut of the questionnaire is presented in Appendix 1.

After the questionnaire data had been obtained, validity and reliability tests were performed to test the eligibility of the items and the accuracy of the questionnaire results. After that, the results of the questionnaire through the corellation and hypothesis tests were used to know the relationship between variables. After being declared valid, reliable and passed hyphotesis, the result of questionnaire quality of the Tokopedia website was analyzed using kano model and Importance Performance Analysis. After getting the results from the kano model, then performed data processing Importance Performance Analysis which showed which indicators need improvement, the design of the improvement of the Tokopedia.com e-commerce website was improved by using the Quality Function Deployment. The design of the improvement was described in the House of Quality where there were several technical characteristics needed for improvement.

4. Results

Based on the result of the questionnaire, the user of the Tokopedia.com website who became the respondents by gender involved in this study were 63% or 65 respondents were female, and the remaining 37% or 38 respondents were male. Meanwhile, seen from the age of respondents, 78% or 81 respondents were 20-30-year-old, 15% or 15 respondents were 31-40-year-old, and 7% or 7 respondents were 41-50-year-old. The types of work of the respondents were private employees 83% or 86 respondents, civil servants 9% or 10 respondents, students 4% or 4 respondents, and housewives 4% or 3 respondents. Based on the frequency of use of e-commerce websites, 19% or 20 respondents regularly used e-commerce website, 50% or 52 respondents frequently used e-commerce websites, and 31% or 31 respondents quite often used e-commerce websites.

4.1. Validity and Reliability Analysis

The following are the results of the validity and reliability tests of the questionnaire results from 103 respondents involved in this study.

Table 1. Validity Test

Questions	R Count Value	R Table Value	Decision
			R Count > R Table
WD1	0.437	0.1638	Valid
WD2	0.716	0.1638	Valid
WD3	0.511	0.1638	Valid
WD4	0.536	0.1638	Valid
WD5	0.320	0.1638	Valid
WD6	0.616	0.1638	Valid
PQ1	0.637	0.1638	Valid
PQ2	0.652	0.1638	Valid
PQ3	0.726	0.1638	Valid
PQ4	0.491	0.1638	Valid
PQ5	0.272	0.1638	Valid
SQ1	0.633	0.1638	Valid
SQ2	0.579	0.1638	Valid
SQ3	0.632	0.1638	Valid
SQ4	0.524	0.1638	Valid
SQ5	0.738	0.1638	Valid
DQ1	0.615	0.1638	Valid
DQ2	0.342	0.1638	Valid

Table 1. Validity Test (Continue)

Questions	R Count Value	R Table Value	Decision
			R Count > R Table
DQ3	0.731	0.1638	Valid
DQ4	0.726	0.1638	Valid
DA5	0.387	0.1638	Valid
DQ6	0.208	0.1638	Valid
DQ7	0.487	0.1638	Valid
DA1	0.544	0.1638	Valid
DA2	0.632	0.1638	Valid
DA3	0.404	0.1638	Valid
DA4	0.685	0.1638	Valid
DA5	0.466	0.1638	Valid
CS1	0.251	0.1638	Valid
CS2	0.210	0.1638	Valid
CS3	0.265	0.1638	Valid
CS4	0.251	0.1638	Valid
CS5	0.716	0.1638	Valid
CS6	0.670	0.1638	Valid
PS1	0.618	0.1638	Valid
PS2	0.526	0.1638	Valid
PS3	0.620	0.1638	Valid
PS4	0.684	0.1638	Valid
PS5	0.562	0.1638	Valid

Table 1 presents the results of the SPSS 25.0 calculation regarding the overall value of *r* count which is greater than the r table value of 0.1638 for 103 questionnaires. Consequently, it can be concluded that the whole question items in the questionnaire are valid. After that, a reliability test was made to measure the reliability of respondents' responses to the general items of the questions asked. According to Santoso (2010), the questionnaire is deemed to be reliable if the value of the Cronbach Alpha is above 0.60. The following are the results of the reliability test of 39 question items in the questionnaire.

Table 2. Reliability Test

Question Items	Alpha Cronbach	Description
39	0.931	Reliable

Based on the calculation using SPSS 25.0 presented in Table 2 above, it can be inferred that the Cronbach Alpha coefficient value is 0.931. Thus, it can be concluded that the question items in the Tokopedia.com e-commerce website quality questionnaire had a good level of consistency. Therefore, the findings of this study can be accounted for and can be used for further data processing to provide solutions for improving the quality of e-commerce websites.

4.2. Corelation Analysis

The relationship between each variable is referred to as correlation. Correlation refers to how a change in one variable causes a change in the direction of another variable. The higher the correlation, the closer the absolute value is to one. As a result, "+" indicates a positive change direction, while "-" indicates a negative change direction. The following is a correlation test between variables where all the dimensions of the tested variables are correlated or have a relationship between variables, since the value of the correlation test results is <0.05 or there are ** and * signs appeared in Table 3.

Table 3. Correlations Test

	WD	PQ	SQ	DQ	DA	CS	PS
	1						
WD							
	103	103					
	.680**	1					
PQ	0						
	103	103	103				
	.529**	.577**	1				
SQ	0	0					
	103	103	103	103			
	.608**	.705**	.707**	1			
DQ	0	0	0				
	103	103	103	103	103		
	.487**	.588**	.858**	.683**	1		
DA	0	0	0	0			
	103	103	103	103	103		
	.200*	.228*	0.19	.233*	.249*	1	
CS	0.043	0.021	0.055	0.018	0.011		
	103	103	103	103	103	103	
	.739**	.637**	.748**	.718**	.743**	.294**	1
PS	0	0	0	0	0	0.003	
	103	103	103	103	103	103	103

** Correlation is significant at the 0.01 (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

4.3. Hypothesis Analysis

Hypothesis testing aims to test the effect of the quality of the Tokopedia.com website on customer satisfaction. The hypothesis was tested using regression analysis by determining seven sub-factors as independent variables, with customer satisfaction as the dependent variable. The regression analysis hypothesis test results, which are attached in Table 4, are as follows.

Table 4. Hypothesis Test

	Unstandardized Coefficients		Standardized Coefficients			Adj R2
	B	Std. Error	Beta	T	Sig.	
(Constant)	-2.156	1.141		-1.889	0.062	0.996
WD	1.193	0.056	0.226	21.435	0.000	
PQ	1.034	0.060	0.173	17.128	0.000	
SQ	0.933	0.078	0.160	12.029	0.000	
DQ	1.144	0.055	0.225	20.968	0.000	
DA	1.185	0.082	0.191	14.398	0.000	
CS	1.235	0.071	0.115	17.329	0.000	
PS	0.957	0.078	0.159	12.250	0.000	

Hypothesis 1 predicts that the Website Design (WD) positively influences consumen satisfaction. The regression analysis of Hypothesis 1 has P=0.000<0.05, indicating a statistically significant correlation. Thus, Hypothesis 1 is accepted. Hypothesis 2 predicts that the Product Quality (PQ) positively influences consumen satisfaction. The regression analysis of Hypothesis 2 has P=0.000<0.05, indicating a statistically significant correlation. Thus, Hypothesis 2 is accepted. Hypothesis 3 predicts that the Security Quality (SQ) positively influences consumen satisfaction. The regression analysis of Hypothesis 3 has P=0.000<0.05, indicating a statistically significant correlation. Thus, Hypothesis 3 is accepted. Hypothesis 4 predicts that the Delivery Quality (DQ) positively influences consumen satisfaction. The regression analysis of Hypothesis 4 has P=0.000<0.05, indicating a statistically significant correlation. Thus, Hypothesis 4 is accepted. Hypothesis 5 predicts that the Delivery Accuracy (DA) positively influences consumen satisfaction. The regression analysis of Hypothesis 5 has P=0.000<0.05, indicating a statistically significant correlation. Thus, Hypothesis 5 is accepted. Hypothesis 6 predicts that the Customer Service (CS) positively influences consumen satisfaction. The regression analysis of Hypothesis 6 has P= 0.000<0.05, indicating a statistically significant correlation. Thus, Hypothesis 6 is accepted. Hypothesis 7 predicts that the Customer Perception and Satisfaction (PS) positively influences consumen satisfaction. The regression analysis of Hypothesis 7 has P=0.000<0.05, indicating a statistically significant correlation. Thus, Hypothesis 7 is accepted.

4.4. Kano Model and Importance Performance Analysis

The Kano model was analyzed to determine the attributes that customers need as well as those that have the potential to become a source of innovation for the Tokopedia.com website. Each respondent's questionnaire was categorized into M (Must be), O (One dimensional), A (Attractive), I (Indifferent), R (Reserve), and Q (Questionable). After collecting 103 respondents, then the results of the number of each service attribute are calculated. Data processing in the Kano model for each attribute is determined by the following rules, namely if (M+O+A)>(I+R), then the service attribute category is max (O, A, M) and if (M+O+A)<(I+R), then the Kano's category for the service attribute is max (I, R). Table 5 summarizes the results of the Kano model calculation.

Table 5. Kano Model

No	Code	M	O	A	I	R	Q	M+O+A	I+R	Kano Category
1	WD1	61	29	12	0	0	1	102	0	M
2	WD2	73	18	10	2	0	0	101	2	M
3	WD3	41	7	52	1	0	2	100	1	A
4	WD4	37	45	21	0	0	0	103	0	O
5	WD5	42	50	9	1	0	1	101	1	O
6	WD6	28	59	16	0	0	0	103	0	O
7	PQ1	51	37	12	2	0	1	100	2	M
8	PQ2	59	33	11	0	0	0	103	0	M
9	PQ3	40	18	44	1	0	0	102	1	A
10	PQ4	32	31	39	0	0	1	102	0	A
11	PQ5	37	25	41	0	0	0	103	0	A
12	SQ1	46	53	4	0	0	0	103	0	O
13	SQ2	35	67	1	0	0	0	103	0	O
14	SQ3	31	48	15	2	0	7	94	2	O
15	SQ4	20	52	31	0	0	0	103	0	O
16	SQ5	48	41	6	4	1	3	95	5	M
17	DQ1	62	37	4	0	0	0	103	0	M
18	DQ2	59	12	30	1	0	1	101	1	M
19	DQ3	47	50	6	0	0	0	103	0	O
20	DQ4	36	21	39	3	0	4	96	3	A
21	DQ5	42	39	19	2	0	1	100	2	M
22	DQ6	38	55	10	0	0	0	103	0	O
23	DQ7	49	31	22	1	0	0	102	1	M
24	DA1	41	58	4	0	0	0	103	0	O
25	DA2	40	43	19	0	0	1	102	0	O
26	DA3	28	47	26	0	0	2	101	0	O
27	DA4	55	38	10	0	0	0	103	0	M
28	DA5	59	41	3	0	0	0	103	0	M
29	CS1	51	26	25	1	0	0	102	1	M
30	CS2	63	19	21	0	0	0	103	0	M
31	CS3	57	28	17	0	0	1	102	0	M
32	CS4	40	53	10	0	0	0	103	0	O
33	CS5	31	49	23	0	0	0	103	0	O
34	CS6	34	52	17	0	0	0	103	0	O
35	PS1	59	40	4	0	0	0	103	0	M
36	PS2	41	11	43	5	0	3	95	5	A
37	PS3	38	9	51	5	0	0	98	5	A
38	PS4	42	31	19	11	0	0	92	11	M
39	PS5	35	20	33	12	1	2	88	13	M

According to Table 5, there are 17 attributes that are categorized as Must be (M), 15 attributes are categorized as One dimensional (O), and 7 attributes are categorized as Attractive (A) which means that all attributes are included in the categories M, O, and A which are tested, affect consumer satisfaction of e-commerce website users, while there are no attributes that fall into category I or R, which means that there is not a single attribute that does not affect customer satisfaction.

Therefore, in the next IPA processing, all attributes will be analyzed. The results of the IPA analysis, as shown in Figure 1, are as follows.

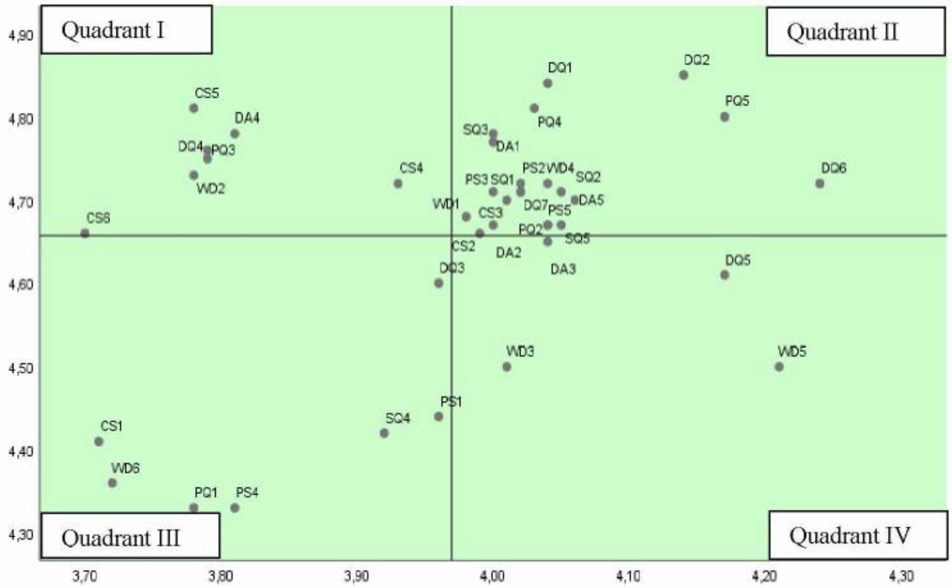

Figure 1. Importance-Performance Analysis

The items included in quadrant I were item WD2 with indicator the information on the website is effective, item PQ3 with indicator all products on the website are available, item DQ4 with indicator the websites offers discount or free shipping, item DA4 with indicator delivers products in accordance with the set conditions, item CS4 with indicator it provides me with convenient options for returning items, item CS5 with indicator this site handles products returns well, and item CS6 with indicator return policy is simple. After analyzing the questionnaire using the kano model and Importance-Performance Analysis (IPA) so that it is known which items need to be repaired (quadrant I), an improvement design using Quality Function Deployment (QFD) by arranging House of Quality.

4.5. Quality Function Deployment

The first phase in preparing QFD was the matrix of consumer needs or Voice of Customer which was a list of items that were important to consumers. In this study, the results of Importance Performance Analysis (IPA) were used in determining the Voice of Customer by placing the items in quadrant I like the focus of improvement. Phase 2 was determining the ratio of improvement of each quality indicator on the Tokopedia.com website. To achieve desirable and measurable results, targets were measured as well. The following is the formula for calculating the value of the improvement ratio.

$$IR = \frac{Expectation\ (Target\ Value)}{Perception\ (Performanse)} \quad (1)$$

Using this formula, the determination of the improvement ratio was done by comparing the expected value with the perception obtained from the results of the questionnaire. The calculation of the improvement ratio in quadrant I items was as follows.

Table 6. Improvement Ratio

Code	Indicator	Expectation	Perception	Improvement Ratio (IR)
WD2	The information on the website is effective	4.73	3.78	1.25
PQ3	All products on the website are available	4.76	3.79	1.26
DQ4	The website offers discount or free shipping	4.75	3.79	1.25
DA4	Delivers products in accordance with the set conditions	4.78	3.81	1.25
CS4	It provides me with convenient options for returning items	4.72	3.93	1.20
CS5	This site handles product returns well	4.81	3.78	1.27
CS6	Return policy is simple	4.66	3.70	1.26

The third phase was determining the technical characteristics. Technical characteristics are the response given by the company to user desires that need to be revised. Determination of the technical characteristics was conducted by benchmarking, discussion, and interviews with interested parties. Determination of technical characteristics included various features of the website, standards for completeness of information, consistency in implementing SOPs, refund policies, Labor qualifications, and availability of assurance products. The fourth phase was the benchmarking stage which was conducted by comparing Tokopedia.com e-commerce with similar companies. The fifth phase was the relationship analysis of what's and How's Matrixes. In this section, the researchers described the relationship between customer needs and the technical characteristics needed to meet customer needs. This section was marked with number 3 which means it had a positive correlation and number 9 which means strong positive. The analysis of the relationship between what and how matric is presented in Appendix 2.

The sixth phase was determining the correlation of technical characteristics drawn on the roof of the House of Quality. Characteristic correlations were described by four symbols, including the black circle symbol that represented a strong positive relationship and the white symbol that represents a positive relationship. Additionally, a negative relationship was depicted by a black triangle symbol which means strong negative and white triangle which means negative. Further, the seventh phase was setting goals or targets for each technical characteristic which means the steps or strategies needed for the organization to achieve the specified technical features. The following were the targets or stages that have to be carried out to achieve the required technical characteristics.

Table 7. Target or Limit Value

Technical Characteristic	Target
Variety of Website Features	There are features about product info, shipping refunds, payment, and expedition tracking features
Completeness of Information	Providing direction to the seller in the procedure of providing information in marketing their product
Consistency in SOP Implementation	Providing strict standards and consequences for parties related to customer sevice or the seller in carrying out duties or regulations in selling products
Refund Policy	The website provides a good refund policy
Labor Qualification	Providing training to customer service websites
Assurance Availability	Providing a guarantee of products purchased by customers if something goes wrong

Next, the final phase was determining the priority level. The priority level was used to determine which Target or Limit Value had the highest priority level and the lowest priority level. Technical Priorities is the result of multiplying the values contained in the technical characteristics with the value of importance to customer. The results of the technical characteristic values can be used to calculate the percentage value for total priorities. The greater the value, the greater the priority for improvement. The results of the House of Quality (HOQ) design to improve the quality of e-commerce websites, in the Tokopedia Company is presented in Appendix 3.

5. Discussions

Value of technical priorities is obtained by multiplication between the values of the technical characteristics with the value of importance to customer. Example for calculate Technical Priorities of Variety of Websites Features =(9×5)+(9×5)+(9×5)+(9×5)+(9×5)+(9×5)+(9×5)=315. Example for calculate Percent Total Priorities of Variety of Websites Features=(315/(315+315+315+285+225+285)=18%. Others Technical Priorities and Percent Total Priorities can be calculated as above formula. Based on Appendix 3, determining the top priority in improving website quality based on the value technical priorities became the technical focus of improving the quality of e-commerce websites that have to be done immediately. The technical characteristic with the highest weight was variety of website features, completeness of information and consistency in the implementation of SOP. A variety of website features is various features found on a website designed for marketing needs. Thus, the intended website can meet the desires of the user. Variety of website features where the website must provides features that can accommodate all information related to the product with all its policies. This includes features of the information that is accurate, reliable, timely, and also detailed. The website must provide tracking features for product shipments as well as by phone interaction with the customer service website. The standard of completeness of information in which the seller is most responsible for these characteristics. The standard of completeness of information including websites must provides accurate, reliable, timely, and also detailed information. Additionally, the website has to provide information on product return policies, information on compensation in the event of an internal problem, and also information about the customer service website telephone number.

In case SOP implementation, SOP must was made with strict standards. Moreover, there were consequences if the SOP was not carried out according to the standard. The strict standard was to give obligations to related parties both customer service and seller in complying with the rules in the applicable SOP. SOP on customer service including the ability of customer service website as a good mediator in the event of the return of goods between the seller and buyer, the ability of customer service in resolving the problem immediately, the ability of customer service in providing a solution in the form of compensation in the event of an internal problem, and interacting directly with the users. Meanwhile, according to the SOP, the seller is required to provide accurate, reliable, up to date, and detailed information.

The second-highest weighted technical characteristic was refund policy and assurance availability. Refund policy was in effect for the product received which was not following the expectation of the buyer, such as a product in a defective condition, inadequate quantity, wrong color, and so on. The indicators included in the refund policy were product returns according to applicable regulations, immediately handled by the customer service, the existence of compensation, and the ease of communication between the user and the customer service website. The indicator required to be reviewed to prevent refunds was the website. In this case, the seller has to provide accurate and reliable information to minimize product returns. An assurance on the website is a guarantee given by the Tokopedia.com website when things go wrong. The indicators included in this regard are the website handling product returns well, as well as being able to provide compensation in the event of an internal problem. Indicators that also need to be reviewed were if the website does not provide accurate, reliable, and timely information, in addition to that if the customer service does not resolve the problem immediately and is also difficult to contact.

The third-highest weighted technical characteristic was labor qualifications. Employees were the spearhead of the website quality delivery system. For employees to be able to meet the expectations of website users effectively, it requires support from the main management functions. This support can be in the form of equipment, information, and training in service standards. Indicators included in terms of workforce qualifications were handling product returns properly, addressing problems immediately, and also the ease of communicating with customer service websites wither through chat or by phone features.

6. Conclusion

Based on the results of the integration of the Kano and IPA models, it has been proven effective in knowing which attributes need to be improved in enhancing the quality of the e-commerce website Tokopedia.com. Furthermore, there are seven attributes that need to be improved out of the 39 attribute studied. The Kano and IPA models' results for these seven attributes have a significant effect on customer satisfaction, but they are not as expected.

The seven attributes are the information on the website is effective, all products on the website are available, the website offers discount or free shipping, delivers products in accordance with the set conditions, it provides me with convenient options for returning items, this site handles product return well, and return policy is simple. The seven attributes that do not meet customer expectations are then evaluated with QFD, which results in a technical analysis that needs to be improved, including a variety of website quality, standard of completeness of information, consistency of SOP implementation, refund policy, workforce qualifications, and assurance availability. The integration of the Kano and IPA models can be used for future research with a larger sample size. Furthermore, additional research must be capable of analyzing two or more related e-commerce websites.

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Appendix 1. Dimensions & Items

Dimension	Code	Attributes	Reference
Website Design (WD)	WD1	The website adequately meets my information needs	Blut, M. (2016)
	WD2	The information on the website is effective	Blut, M. (2016)
	WD3	The website is visually pleasing	Blut, M. (2016)
	WD4	The display pages within the website are easy to read	Blut, M. (2016)
	WD5	The text on the website is easy to read.	Blut, M. (2016)
	WD6	The website loads quickly	Blut, M. (2016)
Product Quality (PQ)	PQ1	This website has a good selection products	Blut, M. (2016)
	PQ2	The site has a wide variety of products that interest me	Blut, M. (2016)
	PQ3	All products on the website are available	Blut, M. (2016)
	PQ4	The website offers discount product	Blut, M. (2016)
	PQ5	The website has lower prices than offline stores	Blut, M. (2016)
Security Quality (SQ)	SQ1	I feel safe in my transactions with the website	Blut, M. (2016)
	SQ2	The website has adequate security features	Blut, M. (2016)
	SQ3	This site protects information about my credit card	Blut, M. (2016)
	SQ4	I trust the website to keep my personal information safe	Blut, M. (2016)
	SQ5	It protects information about my web-shopping behavior	Blut, M. (2016)
Delivery Quality (DQ)	DQ1	The product is delivered by the time promised by the seller	Blut, M. (2016)
	DQ2	This website makes items available for delivery within a suitable time frame	Blut, M. (2016)
	DQ3	It quickly delivers what I order	Blut, M. (2016)
	DQ4	The website offers discount or free shipping	Blut, M. (2016)
	DQ5	Seller provides delivery at low cost	Vasic, et al. (2020)
	DQ6	Seller delivers products in accordance with the set conditions	Vasic, et al. (2020)
	DQ7	The website offers the shipment tracking option	Vasic, et al. (2020)
Delivery Accuracy (DA)	DA1	You get what you ordered from this website	Blut, M. (2016)
	DA2	The website is truthful about its offerings	Blut, M. (2016)
	DA3	The ordered products arrived in a good condition	Blut, M. (2016)
	DA4	Delivers products in accordance with the set conditions	Vasic, et al. (2020)
	DA5	Shipment content is seldom liable to complaints	Vasic, et al. (2020)
Customer Service (CS)	CS1	This site provides a telephone number to reach the company	Blut, M. (2016)
	CS2	This site has customer service representatives available online	Blut, M. (2016)
	CS3	It offers the ability to speak to a live person if there is a problem	Blut, M. (2016)
	CS4	It provides me with convenient options for returning items	Blut, M. (2016)
	CS5	This site handles product returns well	Blut, M. (2016)
	CS6	Return policy is simple	Vasic, et al. (2020)

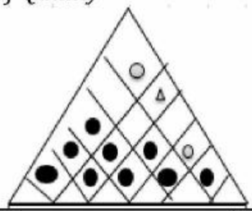
Appendix 1. Dimensions & Items (Continue)

Dimension	Code	Attributes	Reference
Customer Perception and Satisfaction (PS)	PS1	I am satisfied with this online retailer	Blut, M. (2016)
	PS2	The online retailer always meets my needs	Blut, M. (2016)
	PS3	I consider this online retailer to be my first choice for next transactions	Blut, M. (2016)
	PS4	I say positive things about this online retailer to other people	Blut, M. (2016)
	PS5	I recommend this online retailer to someone who seeks my advice	Blut, M. (2016)

Appendix 2. How and What Matrix

Code	Primary / Technical Charasteristic	1 Variety of Website Features	3 Completeness of Information	4 Consistency in SOP Implementation	5 Refund Policy	6 Labor Qualification	7 Assurance Availability
WD2	The information on the website is effective	9	9	9	9	9	3
PQ3	All products on the website are available	9	9	9	9	3	9
DQ4	The website offers discount or free shipping	9	9	9	3	3	9
DA4	Delivers products in accordance with the set conditions	9	9	9	9	3	9
CS4	It provides me with convenient options for returning items	9	9	9	9	9	9
CS5	This site handles product returns well	9	9	9	9	9	9
CS6	Return policy is simple	9	9	9	9	9	9

Appendix 3. House Of Quality



	Code	Technical Charasteristic	Variety of Website Features	Completeness of Information	Consistency in SOP Implementati	Refund Policy	Labor Qualification	Assurance Availability	Customer: Tokopedia	Competitive: Competito	Importance to Customer	Improvement Ratio	Sales Point
		Technical Descriptors (HOWs)											
		Primary	1	3	4	5	6	7					
Customer Requirements (WHATs)	WD2	The information on the website is effective	9	9	9	9	9	3	4	4	5	1.3	1.5
	PQ3	All products on the website are available	9	9	9	9	3	9	4	4	5	1.3	1.5
	DQ4	The website offers discount or free shipping	9	9	9	3	3	9	4	4	5	1.3	1.5
	DA4	Delivers products in accordance with the set conditions	9	9	9	9	3	9	4	4	5	1.3	1.5
	CS4	It provides me with convenient options for returning items	9	9	9	9	9	9	4	4	5	1.3	1.5
	CS5	This site handles product returns well	9	9	9	9	9	9	4	4	5	1.3	1.5
	CS6	Return policy is simple	9	9	9	9	9	9	4	4	5	1.3	1.5
Technical Competitive		Tokopedia	4	4	4	4	3	4					
		Competitor	4	4	4	4	4	4					
Degree of Technical Difficulty			7	7	9	7	7	7					
Target Value			5	5	5	5	5	5					
Absolute Weight and Percent			315	315	315	285	225	285					
% Total Priorities			18	18	18	16	13	16					
			Prioritized Technical Descriptor										

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RANKING VALUE-CREATING GREEN APPROACH PRACTICES AND CHOOSING IDEAL GREEN MARKETING STRATEGY FOR LOGISTICS COMPANIES

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Abstract: *The deterioration of environmental factors, economic and technological development, the formation of complexity in societies, the rise of complex structures have made the environment and green management practices more important. Especially value-creating green approaches are considered as critical components in both public and private sector applications and defined as indicators of success in terms of sustainability. On the other hand, green marketing strategies are also important practices that have a positive impact on the environment and should be carefully emphasized for the inheritance of nature to future generations. Recently, it has been on the agenda quite a lot and it is understood for all sectors.In this study, it is aimed to determine the criteria for value-creating green approach practices in logistics companies operating in the TR A1 region due to the above mentioned importance and to choose the most ideal green marketing strategy. In solving this problem, Multi Criteria Decision Making (MCDM) methods, which are a complex decision-making method, have been used. According to the results of the research, it was determined that the most important criterion in value creating green approach applications as Environmental Focused Strategic Decisions (C3), and the least important criterion as Environmental Life Cycle Analysis (C2). It has been determined that the most ideal green marketing strategy is Green Innovation (A1). Accordingly the importance of the environmental based strategic decisions is revealed in terms of creating green marketing strategy for companies.*

Key words: *Green Approaches, Value Creating Green Approaches, Green Marketing Strategy, ENTROPY, MAUT.*

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1. Introduction

Nowadays, waste and gas emissions generated by supply chains are a major source of serious environmental problems, leading to global warming and acid rain (Bloemhuf et. al., 1995). Within the scope of supply chains, various studies are carried out to minimize the damages to the ecosystem. With globalization, solutions in all areas of supply chains have increased. These fields are; environmental compliance requirements, supply chain requirements and consumer demands, sustainability and corporate social responsibility projects (Shecterle and Senxian, 2008).

In addition to reducing costs in a competitive market environment, businesses were forced to adopt more environmentally friendly policies as a result of the Kyto Protocol signed in 1997. Logistics is one of the main operations of the company. For this reason, logistics is costly and damages the environment. The purpose of green logistics is to reduce the environmental impacts of businesses while continuing their logistics activities.

Environmental negativities related to global warming in recent years have caused consumers to take part in activities aimed at protecting the environment. As a result, consumers began to act in a way that could affect their purchasing process. Therefore, it has become necessary for companies to change their business models in order to adapt their activities to green trends. The decision theory approach has become an important tool for providing real-time solutions to uncertainty problems, especially for sustainable engineering and environmental sustainability problems in engineering processes (Stojčić et al, 2019).

Perceived value is the value that the product or service has in the mind of the consumer. In other words, it is a consumer's general assessment of net benefit (Bolton & Drew, 1991; Patterson & Spreng, 1997). Based on this definition, green value, which is a new concept for this study, It can be expressed as the evaluation of a product or service consisting of the net benefit between what is received and what is given according to the consumer's environmental desires, sustainable expectations and environmentally sensitive needs.

Green logistics is an issue that has recently developed and become widespread in the transportation sector. The world's leading transport companies have begun to transition to green logistics since the early 2000s and local companies since 2010. Along with the laws and incentives applied in developed countries, railway, maritime and inland waterway transportation has also been used as a substitute for the road.

Green marketing activities are carried out with support from all relevant departments of the business in order to focus on customer needs and values. The adoption of a green marketing strategy is reorienting a business in terms of how it launches and manages its green practices, It also affects how it reacts to rapidly growing green customer demand and changes in dynamic market conditions, how it targets its customers, how it promotes market offers and how it uses green initiatives to create a sustainable competitive advantage (D'Souza et al., 2015). While applying green marketing strategies of businesses; It is important for them to know how to initiate and manage green activities, define their target customers, and encourage market resources to benefit from green activities in building sustainable competitiveness (Shi & Yang, 2019).

In an environment where competition is increasing, in order to gain competitive advantage, it is very important to integrate green marketing practices with every function of the business for a trustworthy corporate reputation, a green image for trustworthy corporate reputation, green marketing strategies to create a green image and strong green marketing strategies. In particular, green approaches that create value are seen as critical components in both public and private sector applications and are defined as indicators of success in terms of sustainability. In this context, determining the difficult and value-creating green approach marketing strategies, which is a complex process, and combining multiple variables to make decisions can be considered as a problem.

Firms need to be careful in creating green products and services and differentiating from competitors before selecting the green marketing strategies. That complicates the process of selecting and applying profitable green marketing strategy by managers too. Hence it is important to form value creating green marketing strategies for managers. In this context, it was aimed to determine the criteria for value-creating green approach practices in logistics companies operating in the TR A1 region (covering the provinces of Erzurum, Erzincan and Bayburt in northeastern region of Turkey) and to choose the most ideal green marketing strategy. Reasons for selecting the region of TRA1 are recent positive foreign trade based developments and the positive effects on the logistic activities. According to the authors' view there is not any study in the literature which aims to prioritize the value creating green approach practices and select the most ideal green marketing strategy with respect to logistics companies, and that shows the originality and novelty of the work.

The criterion weights were determined by the ENTROPY method and the MAUT Method was used in the selection of the most ideal green marketing strategy. In the later stages of the study, a detailed literature review was made for green values and green marketing strategies, ENTROPY and MAUT Method were applied to the study, and the study was completed with the Results and Recommendations section.

2. Literature Review

A detailed literature review on the value creating green approach and green marketing strategies is given below:

Confente and Ruso (2009) argued that the recyclability of products and packaging and the creation of limited spaces for logistics applications are examples of green logistics practices. Lopes et al. (2010), green value indicators are based on the certification of environmental management system, reducing energy consumption and using renewable energy. In addition, it is seen that product and packaging refer to environmentally friendly and coordinated transportation to recycling by acting with green awareness in product design. As a result of a study conducted by Hu and Hsu (2010) on companies in Taiwan, green supply chain implementation has been dealt with in four dimensions: supplier management, product recycling, enterprise relationship and life cycle management. Kim and Han (2011) demonstrated that both freight transport and storage actions are among the green logistics indicators. Zhang and Zhao (2012) demonstrate the importance of disposal of waste within the enterprise, stating that measures should also be taken for freight transport. Evangelista et al. (2012), it is seen that the legal regulations and the actions related to freight transportation are added to the green logistics indicators. According to Seroka (2014), it connects green logistics indicators to the cooperation between product designer and supplier, environmental cooperation with customers, legal regulations, green design and reverse logistics. Wichaisri and Sopadang (2014) showed that activities aiming to minimize waste rate, intermodal transportation systems, cargo transportation activities and raising awareness of the organizational structure are among the green logistics indicators. Jaller et al. (2015), in addition to the legal regulations, the use of environmentally friendly vehicles and intermodal transport systems and the prevention of traffic congestion that may occur during the distribution of the cargo are presented as green logistics indicators. Atrek and Özdağoğlu (2016) provided data on the current status of green supply chain applications in the aluminum joinery sector in İzmir. As a result of the study, it was concluded that green supply chain applications are not at the desired level and should be developed. Zengin (2017) examined the effects of green logistics practices in sustainable development and aims to evaluate the situation in Turkey on green logistics. There are businesses that consider the practice green logistics in Turkey. Korucuk (2018) determined the effect of green logistics applications on the competitiveness and hospital performance with the application it has applied to 31 public-private-university hospitals operating in Ankara. Korucuk and Memiş (2019) have been prioritized by determining the performance factors of green port practices in enterprises that have received a green port certificate in Istanbul.

Research on green marketing strategies, on the other hand;

Kumar et al. (2012), as a result of their study, emphasized the necessity of including environmental awareness in this process while developing the strategies of businesses that want to be successful in an intense competitive environment.

Leonidou et al. (2013) In a study on hotel businesses operating in Greece, it was concluded that green marketing strategies can provide a competitive advantage, especially for hotel businesses operating in a highly competitive environment. Nadanyiova et al. (2013), in their study on small, medium and large-scale enterprises operating in Slovakia, stated that the inclusion of green marketing activities in the business processes of the enterprises will provide a competitive advantage against their competitors.

Eneizan et al. (2016) stated that green marketing strategies are effective on perceived business performance. Simao and Lizboa (2017), in their research on Toyota, determined that maintaining their activities in an environmentally conscious manner will provide them with some advantages such as low cost, improvement of production process, and increasing the corporate image.

Karimi et al. (2017) tried to bring together the proposed two-stage messenger problem and supplier selection problem in a green supply chain, where the seller must select suitable suppliers to purchase raw materials and finished products. It is assumed that the seller has several types of vehicles that can send them to receive raw materials purchased from selected suppliers. It is also assumed that the greenhouse gas (GHG) emissions emitted by vehicles depend on the total distance between vendors and suppliers. A limitation on the total GHG emissions of selected vehicles is also considered. The aim of the study is to maximize the expected total vendor profit relative to the total cost of supplier selection and the total transportation cost of vehicles subject to budget and storage space constraints. As a result of the calculations, it has been shown that an increase in the number of raw materials will cause a decrease in the purchased quantity of each raw material and final product at the beginning of the sales period.

Suresh et al. (2018) investigated the attitudes of consumers towards environmentally friendly products developed by the e-commerce site Tamil Nadu business towards green marketing strategies. Dzulkarnain et al. (2019), using SWOT analysis, aimed to formulate a green marketing strategies that can be applied in local private agricultural industry development.

Gedik (2020), the existence of environmental strategies of the enterprise; It aimed to measure whether it differs according to green marketing practices, environmental protection studies, elements of the green marketing mix, environmental responsibilities and customer relations.

Kumar and Rodrigues, (2020) considered two UK-based manufacturing companies. One of them is semiconductor manufacturing company (case A) and other is furniture manufacturing company (Case B). Case A and Case B are considered 'polar types' and are similar in different respects. They are similar in their commitment to integrating lean and green practices and have formed cross-functional teams to maximize the potential benefits from the integrated approach. They found that the real benefit of integrated lean and green practices can be realized when a cross-functional team works together across organizational boundaries from design to product delivery and after-sales service.

Handoko et al. (2021) made a case study of the pallet problem for the pulp and paper industry in Indonesia. They aimed to establish pallet material strategy and innovation using the concept of Reduce, Reuse and Recycle (3R) in the pallet supply unit to meet the needs of the production unit and avoid product delivery delays. In a closed-loop system, (solid) finished products were sent to consumers on wooden pallets, and the pallets were stored and reused at the consumer's site for later return (to the manufacturer); pallets used can carry a payload of more than 600 kg. With this green approach, it is aimed to overcome the pallet shortage of the pulp and paper manufacturing industry.

The fact that there is no study on value-creating green approach practices and choosing the most ideal green marketing strategy in the detailed literature review makes the subject valuable. On the other hand, it is thought that the study will contribute to the literature in terms of the field of application and the methods used.

In TR A1 region, ENTROPI and MAUT, which are among the Multi Criteria Decision Making (MCDM) methods for value-creating green approach practices and choosing the most ideal green marketing strategy, have been utilized. Because MCDM methods; It is one of the methods applied differently from statistical analysis techniques, that is, objective and non-objective factors are evaluated together. Analyzes are carried out within the framework of expert opinions, and at the same time, the study can be shaped according to the opinion of a single expert or a group of experts. (Korucuk, 2019).

3. Methodology

In this section, value creating green approach applications and ENTROPY and MAUT methods used in choosing the most ideal green marketing strategy are explained.

3.1. Entropy

Entropy is one of the weighting methods that reflect reality. Entropy, an effective method used to explain the maximum uncertainty or minimum certainty of the problem, also eliminates human-induced errors. In practice, the smaller the value in the method, the smaller the degree of irregularity (Wu et al., 2011: 5163-5165; Çiçek, 2013: 59; Korucuk et al., 2019).

The application steps of Entropy weight method are given below (Abdullah and Otheman, 2013: 26; Korucuk et al., 2020).

Step 1. Creating the Initial Decision Matrix

For a multi-criteria decision problem with m decision alternatives and n evaluation criteria, an initial decision matrix is created as follows:

$$X_{mxn} = \begin{matrix} X_{11} & X_{12} & \cdots & X_{1j} \\ X_{21} & X_{22} & \cdots & X_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ X_{i1} & X_{i2} & \cdots & X_{ij} \end{matrix} \tag{1}$$

Step 2. Normalization of the Initial Decision Matrix

In the normalization process, the following formulas apply according to whether the criteria are benefit (2) or cost (3):

$$r_{ij} = \frac{x_{ij} - x_j^{min}}{x_j^{max} - x_j^{min}} \qquad i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \tag{2}$$

$$r_{ij} = \frac{x_j^{max} - x_{ij}}{x_j^{max} - x_j^{min}} \qquad i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \tag{3}$$

After the initial matrix is normalized, equation (4) is used by showing R = [rij]mxn in the matrix.

$$P_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} \tag{4}$$

Step 3. Calculation of Entropy Value

The entropy value (Ej) is calculated using the following equation (5):

$$E_j = -k \sum_{i=1}^{m} P_{ij} ln\left(P_{ij}\right) \tag{5}$$

Where k is calculated by the formula $k = (\ln(m))^{-1}$.

Step 4. Calculation of Degree of Differentiation

The degree of differentiation of the entropy value (dj) is calculated using the equation (6):

$$d_j = 1 - E_j ; \forall j \quad (6)$$

Step 5. Calculation of Entropy Weight

The objective weight (Wj) of each criterion is defined according to equation (7):

$$W_j = \frac{d_j}{\sum_{j=1}^{n} d_j} ; \forall j \quad (7)$$

3.2. MAUT

MAUT method is a method used by Fisburn (1967) and Keeney (1974) to find the most useful alternative based on both qualitative and quantitative criteria. This method is aimed at finding the most useful alternative based on both qualitative and quantitative criteria. In fact, in the MAUT method, it is aimed to find the most beneficial alternative by making subjective data computable (Loken & Botterud, 2007). Basically, every decision maker consciously or indirectly tries to optimize by bringing all his perspectives together. The decision maker's preferences are also the utility function represented. The decision maker does not need to know this function at the beginning of the decision-making process, so first he has to build the function. The utility function is a way of measuring preferability or alternatives (Tunca et al., 2016).

In addition, decision makers may not be able to clearly reflect their opinions or express their thoughts clearly in determining the complex structure and relationships of real-life problems. In other words, there may be situations where the criterion values cannot be stated with exact expressions (Ergün, et al., 2020).

In this direction, the steps of the MAUT method are given below (Ishizaka & Nemery, 2013; Talkan and Uygun, 2014 and Ergün, et al., 2020);

Step 1: Determination of Criteria and Alternatives

The criteria (a_n) in the decision problem and the alternatives (x_m) that will help in selecting the criteria should be determined.

Step 2: Determination of Weight Values

Assignment is made to the weight values (w_j) that allow the alternatives to be evaluated correctly and for which priorities are determined. The sum of all (w_j) values must equal 1.

$$\sum_{i=1}^{m} w_j = 1 \quad (8)$$

Step 3: Determining the Decision Matrix

The value measures of the criteria are assigned. This assignment is made by considering paired comparisons for qualitative criteria, while quantitative values are for quantitative criteria. Based on all these, value assignments are made in systems of 5, 100 and so on (xm).

Step 4: Calculation of Normalized Benefit Values

In the normalization process, firstly the best and worst values are determined for each feature and a value of 1 is assigned to the best value and 0 to the worst value. For the calculation of other values, the formula in Equation (9) below is used.

$$f_j\left(a_i\right)=\frac{f_i\left(a_i\right)-min\left(f_i\right)}{max\left(f_i\right)-min\left(f_i\right)} \tag{9}$$

Step 5: Calculation of Total Benefit Values

After the normalization process, the process of determining the benefit values is started. The utility function formula is as in Equation (10).

$$U\left(a_i\right)=\sum_{j=1}^{q} f_i\left(a_i\right).w_j \tag{10}$$

4. Findings

Under this title, a presentation of the findings obtained by applying ENTROPY and MAUT methods for value-creating green approach practices and the most ideal green marketing strategy in the TR A1 Region and the evaluations regarding these findings will be presented. In this study, the criteria for value-creating green approach practices were created by using expert opinions and literature review (Van Hoek, 1999, Sarkis, 2003 and Zhu et al. 2007) and shown in Table 1. Green marketing strategies options are formed (Rodrigue et al., 2001, Kemp and Pearson, 2007, Fargnoli et al., 2012 and Eneizan et al., 2016) are presented in Table 2.

Table 1. Criteria for value-creating green aprroach practices

Criteria	Coded values
Systematic Environmentally Friendly Applications	(C1)
Environmental Life Cycle Analysis	(C2)
Environmental Focused Strategic Decisions	(C3)
Designing Recyclable and Reusable Products	(C4)
Product, Process and Service Valuation	(C5)
Decision Making and Tracking for Environmentally Friendly Products	(C6)
Green Supply Chain Initiative	(C7)

In Table 2 below, green marketing strategy options are given.

Table 2. Alternatives for green marketing strategy

Alternatives	Coded values
Green Innovation	(A1)
Green Logistics	(A2)
Green Pricing	(A3)
Green Design and Positioning	(A4)
Green Segmentation and Targeting	(A5)
Green Communication	(A6)
Green Alliance	(A7)

Academicians (3) who are the stakeholders of the subject; Erzurum (8 managers), Erzincan (4 managers), and Bayburt (2 managers). A total of 17 questionnaires were submitted to the managers of international logistic firms.

4.1. Weighting Criteria

At this stage, the initial decision matrix has been established to evaluate the criteria and seen as Table 3.

Table 3. Initial Decision Matrix for Entropy

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7
C_1	1	7.10	3.63	4.70	4.19	5.49	5.61
C_2	3.34	1	2.76	3.81	5.80	3.39	2.70
C_3	4.56	6.44	1	2.73	2.99	4.13	3.89
C_4	5.15	6.01	6.60	1	3.15	5.44	2.74
C_5	6.44	5.90	3.11	5.04	1	6.10	5.79
C_6	5.33	4.84	2.49	4.19	5.44	1	3.89
C_7	3.17	5.39	3.90	6.15	6.17	3.96	1

Following to that the normalization process is made and the normalized decision matrix is formed as Table 4.

Table 4. Normalized Decision Matrix for Entropy

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7
C_1	0.035	0.193	0.155	0.170	0.146	0.186	0.219
C_2	0.115	0.027	0.119	0.138	0.202	0.115	0.105
C_3	0.157	0.176	0.043	0.099	0.104	0.14	0.152
C_4	0.178	0.164	0.28	0.036	0.11	0.184	0.107
C_5	0.222	0.161	0.132	0.183	0.035	0.207	0.226
C_6	0.184	0.132	0.106	0.151	0.189	0.034	0.152
C_7	0.109	0.147	0.165	0.223	0.214	0.134	0.039

After computing entropy and degree of differentiation values, the objective weights of each criterion are obtained as Table 5.

Table 5. Weights (W_j) of criteria

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7
W_j	0.139	0.128	0.162	0.136	0.151	0.130	0.154

According to Table 5, “Environmental Focused Strategic Decisions”, “Green Supply Chain Initiative”, ”Product, Process and Service Valuation” and “Systematic Environmentally Friendly Applications” were determined as the most important main criteria for internationally qualified logistics companies. On the other hand, the least important criteria were found to be “Environmental Life Cycle Analysis”, “Decision Making and Tracking for Environmentally Friendly Products” and “Designing Recyclable and Reusable Products” respectively.

4.2. Ranking Alternatives

In this section, MAUT method is used to choose the most ideal green marketing strategy. Using the weights of the criteria obtained by the ENTROPY method, the most ideal green marketing strategy was selected with the MAUT method. Each alternative was evaluated using the MAUT questionnaire within the framework of the previously determined decision criteria. During the evaluation, the participants were asked to give each alternative a score of 1-5 (1- worst, 5- best).

Firstly inintial decsion matrix for alternatives in terms of MAUT method is created as Table 6.

Table 6. Initial Decision Matrix for MAUT

Alternatives	C_1	C_2	C_3	C_4	C_5	C_6	C_7
A_1	4	5	3	4	4	5	4
A_2	4	5	3	3	4	4	3
A_3	3	4	4	4	3	4	4
A_4	4	3	3	2	2	2	3
A_5	3	4	2	3	1	2	3
A_6	4	4	1	2	3	5	3
A_7	2	2	3	3	2	3	2

Then normalization process is applied and normalized decision matrix is obtained as Table 7.

Table 7. Normalized Decision Matrix for MAUT

Alternatives	C_1	C_2	C_3	C_4	C_5	C_6	C_7
A_1	1	1	0.667	1	1	1	1
A_2	1	1	0.667	0.500	1	0.667	0.500
A_3	0.500	0.667	1	1	0.667	0.667	1
A_4	1	0.333	0.667	0	0.333	0	0.500
A_5	0.500	0.667	0.333	0.500	0	0	0.500
A_6	1	0.667	0	0	0.667	1	0.500
A_7	0	0	0.667	0.500	0.333	0.333	0

Following to that normalized benefit and total benefit values are computed according to the Eqs. (8) and (9) respectively. Matrix containing total benefit values is seen as Table 8.

Table 8. Matrix for Normalized Total Benefit Value

Alternatives	C_1	C_2	C_3	C_4	C_5	C_6	C_7
A_1	0.139	0.128	0.108	0.136	0.151	0.130	0.154
A_2	0.139	0.128	0.108	0.068	0.151	0.087	0.077
A_3	0.070	0.085	0.162	0.136	0.101	0.087	0.154
A_4	0.139	0.043	0.108	0	0.050	0	0.077
A_5	0.070	0.085	0.054	0.068	0	0	0.077
A_6	0.139	0.085	0	0	0.101	0.130	0.077
A_7	0	0	0.108	0.068	0.050	0.043	0

After that the ranking of the alternatives in this context is given in Table 9 as below.

Table 9. Ranking of Alternatives

Alternatives	A_1	A_2	A_3	A_4	A_5	A_6	A_7
U(ai)	0.946	0.758	0.795	0.417	0.354	0.532	0.269
Ranking	1	3	2	5	6	4	7

According to Table 9, where the alternatives are listed, the most ideal green marketing strategy in logistics companies has been "Green Innovation". Other important green marketing strategies were "Green Pricing", "Green Logistics" and "Green Communication", respectively. The least important green marketing strategy has been the "Green Alliance". The other least important green marketing strategies were determined to be the "Green Design and Positioning" and the "Green Segmentation and Targeting", respectively. In this framework, the general ranking of green marketing strategies selection is A1> A3> A2> A6> A4> A5> A7.

5. Sensitivity Analysis

It is important to review the results of the model according to the demands of decision makers and different conditions. An essential component of the review is the detection of alternative ranking sensitivity in terms of varying decision makers' judgments. For this study, a sensitivity analysis was done to present the alternative ranking according to the changes in criteria weight as per the judgments of the decision-makers (Korucuk, 2019). If this level of rationality is demanded from an individual decision-maker, then MCDM methods used as a support to rational decision making should also satisfy the condition (Pamučar et al., 2017) Several scenarios are formed for examining the alternative rankings for sensitivity analysis. While the first scenario assigns equal criteria weights, others allow for the interchange of weights between criteria. The obtained criteria weights for six scenarios are given in the Appendix A. The results for the alternative ranking of the six different scenarios are presented in Table 10.

Table 10. Sensitivity analysis results

Alternatives	A_1	A_2	A_3	A_4	A_5	A_6	A_7
Ranking	1	3	2	5	6	4	7
Scenario 1. Assigning equal weights to all criteria							
Ranking	1	3	2	5	6	4	7
Scenario 2. The interchange between criteria having the highest weight and the lowest weight							
Ranking	1	3	2	5	6	4	7
Scenario 3. The interchange between criteria having the second highest weight and the second lowest weight							
Ranking	1	3	2	5	6	4	7
Scenario 4. The interchange between criteria having the third highest weight and the third lowest weight							
Ranking	1	3	2	5	6	4	7

The results of the sensitivity analysis show a similar alternative ranking for the four different scenarios, an indication of the strength of the study in terms of significance and validity.

6. Discussion

Studies related to value-creating green aprroaches in terms of firms have gained importance in the recent years. In this study, the criteria for value-creating green approach practices in logistics companies operating in the TR A1 region were determined and the most ideal green marketing strategy was chosen. According to the ENTROPY results, Environmental Focused Strategic Decisions (C3) was found as the most important criterion regarding green value creation practices with the opinions of 17 people in total in the field of logistics and companies operating in the TR A1 region (Erzurum, Erzincan and Bayburt). This result is similar to the studies of Van Hoek (1999); Sarkis (2003); Zhu et al. (2007). In the ENTROPY method, the least significant criteria were obtained as Environmental Life Cycle Analysis (C2), Decision Making and Tracking for Environmentally Friendly Products (C6) and Designing Recyclable and Reusable Products (C4).

Besides, Green Innovation (A1) was obtained as the most ideal green marketing strategy and that is similar to the studies of Kemp and Pearson (2007); Lin et al. (2009); Zailani et al. (2011); Weng et al. (2015); Chu et al. (2019). On the other hand this result does not correspond to the studies of Crane (1998); Solvalier (2010); Fargnoli et al. (2012); Yılmazsoy and Schmidbauer (2015).

It is important to integrate the concepts of corporate reputation, green image, green marketing strategies and green marketing applications with the functions of firms in competitive environment. In this context, this study that aims to prioritize the value-creating green approach practices and select the most ideal green marketing strategy differs from others with respect to considered methodology and obtained results.

7. Conclusion and Future Suggestions

Industrialization and consumption culture directly harm the nature to which human is bound by an organic bond and with the realization of the irreversible consequences of this damage, "green activities" are rapidly gaining importance with the realization that the human race will directly affect both the present and future generations. In order to reduce the harm to nature, human based approaches have been abandoned and environmental based approaches have gained importance. In this direction, efforts have been started in order to minimize the harm caused by human beings to the environment in a wide range ranging from individuals on a global scale to the state and even to international organizations. Especially in the world, considering that raw material and energy costs are increasing and will continue to increase and these items will constitute the biggest item of production costs, businesses should use sustainability and therefore green marketing strategies. Green marketing strategies create a better working environment in businesses and feed lean practices by improving corporate performance, and although lean management does not focus on pollution, it has a positive effect on green management by ending activities that reduce environmental and productive inefficiencies.

In this study, experts who were thought to be parties to the subject were interviewed, but due to time constraints, the study was conducted in the TR A1 region. So it is difficult to generalize results for other regions of Turkey. With a similar study that will cover wider regions in the future, it may be possible to compare the results of green practices in logistics between regions. On the other hand, the problem addressed in this study can be applied to enterprises or producers operating in different fields on a sectoral basis. Similarly, the impact of different combinations of criteria affecting green logistics activities can be examined in future studies. In addition, this study can be developed in the future by adding fuzzy logic with other multi-criteria decision making and/or other parametric or non-parametric methods, and the results can be discussed by comparing them.

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Appendix: Scenarios for alternative ranking

Table A1. Scenario 1 alternative ranking

	C_1	C_2	C_3	C_4	C_5	C_6	C_7
W_j	0.143	0.143	0.143	0.143	0.143	0.143	0.143

	A_1	A_2	A_3	A_4	A_5	A_6	A_7
U(ai)	0.953	0.763	0.786	0.406	0.359	0.548	0.263
Ranking	1	3	2	5	6	4	7

Table A2. Scenario 2 alternative ranking

	C_1	C_2	C_3	C_4	C_5	C_6	C_7
W_j	0.139	0.162	0.128	0.136	0.151	0.130	0.154

	A_1	A_2	A_3	A_4	A_5	A_6	A_7
U(ai)	0.957	0.769	0.784	0.405	0.366	0.555	0.246
Ranking	1	3	2	5	6	4	7

Table A3. Scenario 3 alternative ranking

	C_1	C_2	C_3	C_4	C_5	C_6	C_7
W_j	0.139	0.162	0.128	0.136	0.151	0.154	0.130

	A_1	A_2	A_3	A_4	A_5	A_6	A_7
U(ai)	0.946	0.751	0.795	0.410	0.354	0.539	0.269
Ranking	1	3	2	5	6	4	7

Table A4. Scenario 4 alternative ranking

	C_1	C_2	C_3	C_4	C_5	C_6	C_7
W_j	0.139	0.162	0.128	0.151	0.136	0.130	0.154

	A_1	A_2	A_3	A_4	A_5	A_6	A_7
U(ai)	0.946	0.751	0.800	0.412	0.362	0.522	0.272
Ranking	1	3	2	5	6	4	7

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MODIFIED FAILURE MODE AND EFFECT ANALYSIS APPROACHING TO IMPROVE ORGANIZATION PERFORMANCE BASED ON BALDRIGE CRITERIA- A CASE STUDY OF AN ELECTRO-MEDIC INDUSTRY

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Research paper

Abstract: *Full attention is paid to quality in manufacturing; however, less effort is made to develop the organizational performance, which drives overall manufacturing quality. This research measures performance of one manufacturing company that in 2020 experienced surging in demand and experiencing barriers to social activities due to the pandemic. The evaluation was carried out using seven variables from the Malcolm Baldrige Criteria for Performance Excellence (MBCfPE) which were elaborated into 43 indicators of organizational performance. Weaknesses and strengths of organizational performance were sharpened through focus group discussions with experts and ended with a performance improvement solution with a priority rank based on risk priority numbers (RPN) of the FMEA method. The highest RPN is 567 and 432, respectively, for national standard implementation in a particular product and operational scheme during emergency conditions like the Cov-19 pandemic. This study contributes to Indonesian research that combines questionnaires and FMEA improvement analysis based on the US Baldrige criterion.*

Keywords: *Performance Excellence, Baldrige Criteria, MBCfPE, FMEA.*

1. Introduction

The industrial governance crisis due to COVID-19 has hit almost all countries, regardless of technological reliability, the sophistication of health services, or economic independence. (Ranggajati et al., 2020). According to various studies in the past year, the external aspects of the organization have greatly influenced the organization's performance, be it business in general or specifically in the industrial sector throughout 2020. (Yap, 2020), (Ahlstrom et al., 2020). External aspects that affect organizational performance include socio-economic shocks, political policies, and the environment (Amarkhil, 2019). According to the 2020 UNDP report on the actions of Asia Pacific business people, it was stated that in the period of the Cov-19

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pandemic, 35% of businesses had to lay off staff, 25% postponed orders, 25% had to delay investment, 24% had to decrease wages, 18% reduce service (United Nations Development Programme, 2020). The report from Mckinsey released in early 2021 (Zurich et al., 2021) shows that the companies that have managed to survive are the companies that have succeeded in responding to changes to the challenges of the pandemic during 2020. For example, operational efficiency has decreased, and the company has taken action to cut the budget. Likewise, the use of technology has increased with better technology.

However, those reports did not provide basis of evaluation other than questionnaire. There is research gap between what had been done by the companies in respond to pandemic situation and what was background or reason for chosen actions. This gap requires approaching that put an existing or previous condition as base-line and find improvement in another way using tools that commonly being used by industries. Hence, this phenomenon is developed in this research by conducting studies and evaluating a manufacturing organization's performance during challenging periods. This research selected one organization as the research object, PT-EMB, which is a local industry that focuses on the fabrication and manufacturing of electromedical devices located in the Serpong industrial area, Banten province of Indonesia. This organization has ISO-13485 as the standard for the production quality of several types of medical devices. The company produces Oxygen Generators, which are in high demand during 2020, and the locally made ventilator.

This research is carried out for all organization sections about production, including leadership criteria, strategic planning, customer handling, operational processes, labor factors, knowledge management, and performance measurement. The method chosen is the Baldrige criteria issued by the United States, which is commonly called the Malcolm Baldrige Criteria for Performance Excellence (MBCfPE), containing seven primary variables (NIST, 2020). Large companies typically recognize Baldrige performance measurement because the criteria or variables evaluated represent the overall indicators of organizational performance. Baldrige criteria can be applied to government institutions (H. Anggara & Hasibuan, 2020; Widjajanto et al., 2020), hospitals (Sintari, 2020), education (Thompson & Blazey, 2017), and industries.

The research question in this paper is how to evaluate local business performance during the 2020 pandemic period and what to be improved. Thus, this study's objectives are described as assessing the organization's performance during the 2020 pandemic period using seven Baldrige variables and determining activities that must be improved to increase organizational performance. The baseline is Baldrige criteria version 2019-2020, but this research is intended to find performance improvement instead of performance scoring for award ranking. Data collection, interviews, and discussions were carried out from November 2020 to January 2021.

2. Literature Study

2.1 Baldrige Criteria for Performance Measurement

Baldrige method is a quality management application formally enforced in its home country, i.e., the United States. The US-Congress initiated it in 1987 as a request to Malcolm Baldrige, Commerce Department Secretary. This system was approved by the US President and outlined in the "Malcolm Baldrige National Quality Award Improvement Act of 1987" on August 20, 1987 (Vinyard, 2015). Tens of thousands of companies have adopted the Baldrige method in more than 70 countries in the world. Indonesia also adopted MBNQA and made the Indonesian Quality Award (IQA) an award for corporate performance (Widjajanto et al., 2020). Baldrige criteria consist of seven variables and are elaborated for this research into forty-three (43) indicators below Table 1.

Table 1. Baldrige Variable and Indicators

Criteria		No.	Indicator
Criteria 1	Leadership	1	Management must evaluate the company's vision and mission
		2	Evaluate consistency in vision and mission
		3	Evaluate the organization's code of ethics
		4	Improved work environment
		5	Dissemination of NEW regulations and policies
		6	Evaluate all work according to rules and policies
Criteria 2	Strategic Planning	7	Quality planning
		8	Innovative proposals
		9	Evaluation of strategic planning in day-to-day work
		10	Evaluation of the success/achievement of strategic planning
		11	Flexibility of planning changes
Criteria 3	Customer Focus	12	Evaluate the end-user / customer group
		13	Identify the needs of the customer
		14	Identify customer satisfaction and dissatisfaction
		15	Making decisions related to customer satisfaction
		16	Staff knowledge of the company's main customers
Criteria 4	Measurement, analysis, knowledge management	17	Application of performance measurement methods (KPI)
		18	Performance results as the basis for improvement or change
		19	Alignment of employee and company performance
		20	Job information for all employees
		21	Monitoring, controlling, and recording in the workplace
		22	Use of working procedures and instructions in operating equipment and tools.
		23	All employees know about the company's achievements
Criteria 5	Workforce	24	Teamwork
		25	Support for employee career advancement
		26	Employee performance appreciation
		27	Job security
		28	Evaluate employee commitment
Crite	Operational / Proc	29	Availability of materials, spare parts, and tools
		30	Evaluate the work process according to instructions

Criteria		No.	Indicator
		31	All equipment is operated using approved instructions
		32	Equipment operated by authorized personnel
		33	Evaluate the use of methods and SOPs
		34	Preparation of operational schemes to deal with emergencies such as the Covid-19 pandemic
Criteria 7	Results	35	Production targets are met
		36	Customer satisfaction is met
		37	Financial condition is maintained
		38	Compatibility of competencies with the final product
		39	Efforts to overcome obstacles
		40	Compliance with local industry regulations
		41	Application of national standard for ventilator production
		42	CSR support for the surrounding community
		43	Workplace comfort and safety

Many organizational performance appraisals have been carried out using various methods (Abdollahbeigi & Salehi, 2020). Several countries developed their version of the way by referring to standards or practices that are already popular internationally. For example, the Thai government has tools for performance measurement in their agencies and organizations that adopt ISO and MBNQA (Pengsuwan & Choonhaklai, 2019). Then there is the SIQ, namely the Swedish Institute for Quality which was developed by adopting the MBNQA (Raharjo & Eriksson, 2017). Specifically, in several Asian countries, several articles describe the performance assessment of public service organizations such as the Batu Pahat City Government Office, Malaysia (Kaliannan et al., 2014), four government institution (Custom, Immigration, Land Transport, and Mining) in Malaysia (Ali et al., 2017), Indonesian Jakarta government licensing services (H. Anggara & Hasibuan, 2020) and a performance appraisal in the local government of the United Arab Emirates written by a US researcher (Furst Bowe, 2019) as well as an article on Saudi Arabia Public Service Organization written by UK researchers (Alhaqbani, 2017).

Another study originating from Europe outlines the performance appraisal of public services, namely the Lithuanian public sector, using MBNQA, EFQM & BSC. (Balabonienė & Večerskienė, 2015), Organizations in Sweden (Eriksson et al., 2016), Public and private organizations in Sweden use SIQ (Raharjo & Eriksson, 2017) and the Mayor's Office in Greece (Tasiou, 2017). EFQM is the European Foundation for Quality Management which emerged recently after the popular MBNQA (Balabonienė & Večerskienė, 2015) and Sweden (Eriksson et al., 2016).

2.2 FMEA Method for Evaluating Organizational Performance

Failure Mode and Effect Analysis (FMEA) was first developed in the aerospace industry in the 1960s as a systematic methodology for identifying known and unknown modes of failure, including causes and consequences on the system and verifying risks associated with priority scales for corrective action. (Liu, 2016). The FMEA used in this research is classified as modified FMEA, which is developed according to a particular business organization (Huang et al., 2020). One example is a modified FMEA approach that combines multiple criteria decision making, adding a cost component to the Risk Priority Number (RPN) calculation (Lo & Liou, 2018).

Another example is the management of waste management in health institutions that also use modified FMEA (Ouyang et al., 2021) and FMEA modifications for health services (Shi et al., 2019). A study proving the relationship between risk management and organizational performance found the most important reasons for decreased performance in administrative implementation items through using the FMEA method by looking at cost and time losses (Hezla et al., 2020).

The FMEA stages are briefly described:

- Describes all operational activities,
- Compiling potential problems that could arise,
- Give the list of severity, occurrence, and detectability levels.
- Calculating the risk priority number (RPN).
- RPN = severity (S) x occurrence (O) x detectability (D)
- Compile a list of actions or actions to reduce risk according to the RPN.

The FMEA method is commonly used in industry, including electronic and medical devices. Several previous studies have shown significant results related to the use of this method. The use of FMEA is commonly used in the industry to identify possible failures in the production process. It aims to improve product quality and reliability (Hasbullah et al., 2017). Alternative repairs for each failure are priority improvements shown in the risk priority number (RPN) values (Budi Puspitasari et al., 2017). FMEA can also be combined with the Statistical Process Control (SPC) method, as carried out in a study that analyzed defects in the pulp and paper industry (Putra et al., 2020). Many practitioners use FMEA in the application of Total Productive Maintenance (TPM). A study to optimize machine maintenance using Reliability Centered Maintenance (RCM) and FMEA was conducted to evaluate the highest failures on a single type of machine with deficient availability & reliability values and did not meet production standards. The FMEA method is used to find six engine components with a high failure rate so that improvements can be made that increase the reliability value of the machine (Nugroho et al., 2020). FMEA in the electronics industry, as practiced in mobile phone manufacturing, can trace essential steps in improving the manufacturing process, resulting in reduced failures, reduced industrial costs and improved quality index, and satisfying customers. (Oliveira et al., 2019).

3. Research Method

The stages of this research were started from determining the problem, aim and objectives, develop a methodology, and identifying the organization's profile of the research object. The collection of the profile information was carried out through initial interviews. If the information regarding the profile is sufficient, then placing the performance criteria is carried out through a questionnaire. The questionnaire results will be tested to see the level of correlation and the level of reliability. In Figure 1, a research flow diagram is presented that explains the steps of this research.

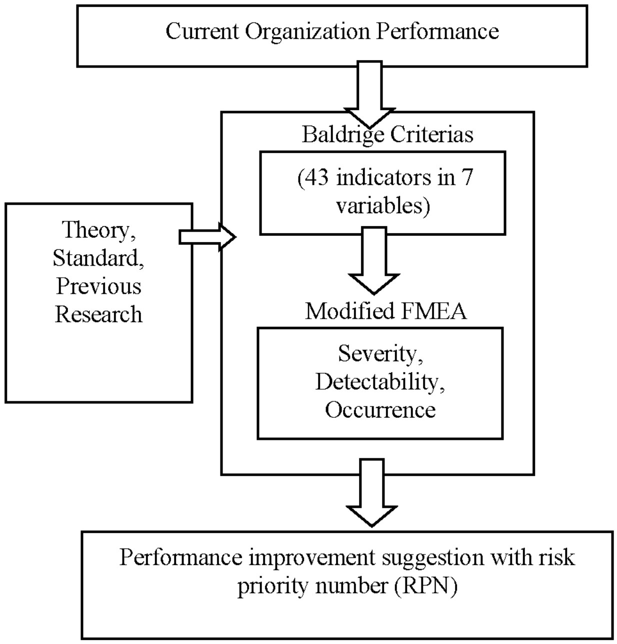

Figure 1. Research Framework

This paper's research aims to evaluate the organizational performance of a local Indonesian electro-medical equipment manufacturing company, which during the Covid-19 pandemic period received a high demand for ventilator and oxygen generator products. The challenges faced, such as social restrictions, logistical difficulties, and other obstacles, will be analyzed in depth. Evaluating the organization's performance is continued by looking for improvement opportunities to improve its organizational capabilities that can compete globally based on the Baldrige criteria used by multinational companies.

This study uses a descriptive exploratory approach using surveys, interviews, and discussions. Based on the Baldrige criteria, organizational performance appraisal produces a scoring used as a baseline as a brief description of the organization's profile. A focus group discussion (FGD) was used with experts selected based on their capabilities. That was part of the brainstorming with the FMEA approach through many performance indicators mapping the organization's condition. The empirical mapping was ranked under the severity, occurrence, and detectability category of the FMEA. The FMEA method makes it easy to adapt to actual situations and presents direct interactions between researcher, respondents, and related experts (Mzougui & El Felsoufi, 2019).

A list of questions was adopted from Baldrige examiner edition 2019/2020 (NIST, 2020) and practical samples (Yusuf, 2017) (Vinyard, 2015). Secondary data is taken from the company in log data related to fabrication activities during the Cov-19 regulation in the form of records and reports obtained that will be helpful in the analysis and determination of corrective steps. The stages in the design of performance improvement are carried out using a modified FMEA approach with the following steps:

- Using the data obtained from Baldrige indicator list.
- Discuss FMEA to find solutions for performance by ranking priorities. The tables for severity, occurrence, and detectability modified by reference are shown in the table below.
- Evaluate and develop potential problems on severity, occurrence, detectability and calculate for respective indicators of Baldrige variables.

4. Data Result and Analysis

4.1 Baldrige Scoring Based on Questionaire

The research questionnaire was distributed to all employees, where the characteristics of the respondents were collected as well age, gender, work experience, education level, and the job position of the respondent. Item Analysis is used to check the validity and reliability of items in measuring variables. These measuring use a Likert scale as the degree of approval of a statement. The questions in the questionnaire used the Baldrige for examiner edition 2019/2020 reference (NIST, 2020). Minitab's item analysis yields the Pearson correlation and Cronbach's alpha values. The Pearson value obtained by Minitab is then compared with the value from the Pearson R critical value table, with a significance of 0.05 and df = 24; the figure is 0.388. If the calculated Pearson correlation value shows a value greater than 0.388, the data is declared valid. Item analysis was carried out to all Baldrige variables and concluded that all survey data is valid and reliable.

Baldrige score on each questionnaire variable, according to H. Anggara & Hasibuan (2020) obtained through the formula:

$$\frac{\left[\frac{\sum n_i w_i}{N.W} x\, 100\%\right]}{Y} \text{ x (Standard score for each Baldrige variable)} \quad (1)$$

n_i = number of respondent for the answer i

w_i = weight of answer i

N = total number of respondents

W = largest answer weight = 5 (Likert scale)

Y = total number of questions for each categorical variable

Calculation and recapitulation of performance scores uses common excel spreadsheets. Its summary is presented in Table 2 as a summary of total scoring. The Baldrige score for the company performance is 463.09 shown in the table. That is equal to 45.86% compared to the ideal Baldrige excellence performance. Obtained a total score of 463.09 is in the Early improvement achievement according to MBNQA award criteria. Criteria 1 until 7 description is available in Table 1 including all relevant question poin.

Table 2 Total Score Baldrige Criteria

Criteria		Score	Ideal MBNQA	Comparison (score/ideal)	Gap	Remarks
1	Leadership	58.00	120	48.33%	2.47%	Strength
2	Strategic Plan	39.44	85	46.40%	0.54%	Strength
3	Customer Focus	39.78	85	46.80%	0.94%	Strength
4	MAKM	39.10	90	43.44%	-2.41%	Weakness
5	Workforce	39.10	85	46.00%	0.14%	Strength
6	Operation	36.67	85	43.14%	-2.72%	Weakness
7	Bussines Result	211.00	450	46.89%	1.03%	Strength
Total	-	463,09	1000	45,86%	-	-

The table also states the gap value obtained from subtraction the obtained score against the average. The negative score on the gap column is classified as weakness, while the positive as strength. The lowest minus value is in criteria no.6 or the Baldrige criteria for operations. That has been labeled as weakness and will be the primary target for corrective action. In that summary, the performance that is considered weak falls also to criteria no.4 Measurement, Analysis and Knowledge Management (MAKM). The leadership or criteria no.1 is superior to the most robust criteria in this company.

4.2 FMEA FGD Result

The next step in finding a performance improvement solution is to quantify the Baldrige performance items by looking at the potential failures of this company. The qualitative performance items are evaluated using a modified FMEA by analyzing the effect of the loss on the schedule, costs, and outputs that impact either major or minor (Harman, 2020; Hezla et al., 2020). The FMEA working paper produced in this research can be classified as a preventive risk assessment method. The results are finding, prioritizing, and removing potential problems as material for improvement and lessons learned in future company activities. (Hezla et al., 2020).

Table 3 (a). Severity Level

Effect	Severity Level	Rank
Schedule	Huge impact, exceeding tolerable limits	
Total Cost	Additional expenses are very significant	9 ~ 10
Technical Problem	Useless output, discarded	
Schedule	Impact on schedule 10-20% of the target	
Total Cost	Additional expenses up to 20% of budget	7 ~ 8
Technical Problem	Output is impacted and cannot be used by the client	
Schedule	Schedule affected up to 10% of target	
Total Cost	Total expenditure costs increased up to 10%	5 ~ 6
Technical Problem	Outputs are impacted and require client approval	
Schedule	Schedule affected, still within tolerance	
Total Cost	Total expenses have increased within tolerance limits	3 ~ 4
Technical Problem	Minor impact and requires internal company approval	
	No effect for all	1~ 2

Table 3 (b). Occurrence Level

Possible Poor Performance	Probability (Occurrence)	Rank
Very high	>1 in 2	10
	1 in 3	9
High (repeatedly)	1 in 8	8
	1 in 20	7

Table 3 (c). Detectability Level

Detectability Assessment	Rank
No detection (of performance measurement) method is available that can alert enough time for corrective action	9 ~ 10
The detection method (of performance measurement) is unreliable or untested. The effectiveness of detection methods is not known for identifying poor performance	7 ~ 8
Performance detection / measurement methods are quite effective in some units / divisions / departments	5 ~ 6
The performance detection/measurement method has been effectively implemented in all work units	3 ~ 4
The performance detection method is very effective, and it is almost certain that poor performance will be detected in a sufficient time	1 ~ 2

In compiling the FMEA, three people were selected as an expert, the first resource person from government representative (X1 or Expert no.1), the second is an academic lecturer (X2 or Expert no.2), and the third expert is person-in-charge General Manager of the company (X3 or Expert no.3). Some references have been used to determine severity level by looking at the effects of the schedule, total costs and technical problems (Liu, 2016) (Hezla et al., 2020) elaborated in Table 3 (a). The level of occurrence and detectability is consecutively in Table 3 (b) and Table 3 (c).

The assessment begins with the information obtained from the Baldrige criteria as the basis for performance items. The points of failure are developed, which can be extracted from the situation in the company that is the object of research and evaluated for possible losses that can reduce the company's organizational performance. Focus on the three main variables of the FGD results that show weak performance. Each item in the variable is assessed severity, occurrence, and detection and calculates risk priority number (RPN). The evaluation results are in Table 4 below and sorted by RPN ranking. Indicator desciprion is available in Table 1 in previous section.

$$RPN = S x O x D \tag{2}$$

RPN: risk priority number
S: severity rank
O: Occurrence rank
D: Detectability rank

Table 4. FMEA result with RPN ranking

Indicator ID No.	X1	X2	X3	S	X1	X2	X3	O	X1	X2	X3	D	RPN	Rank
41	9	9	9	9.00	9	9	9	9.00	7	7	7	7.00	567.0	1
34	9	9	9	9.00	8	8	8	8.00	6	6	6	6.00	432.0	2
29	8	8	8	8.00	8	9	9	8.67	6	6	6	6.00	416.0	3
22	7	7	8	7.33	7	8	8	7.67	8	7	7	7.33	412.3	4
32	7	7	8	7.33	8	8	8	8.00	5	6	6	5.67	332.4	5
31	7	8	8	7.67	8	8	8	8.00	5	5	6	5.33	327.1	6
20	7	7	8	7.33	7	7	8	7.33	5	5	6	5.33	286.8	7
33	7	8	8	7.67	7	7	8	7.33	5	5	5	5.00	281.1	8
36	7	7	8	7.33	7	8	8	7.67	5	5	5	5.00	281.1	9
35	7	8	8	7.67	7	7	7	7.00	5	5	5	5.00	268.3	10
37	7	8	8	7.67	7	7	7	7.00	5	5	5	5.00	268.3	11
40	7	7	8	7.33	7	7	7	7.00	5	5	5	5.00	256.7	12

The results obtained in the table show that the priority which has the potential to become a significant problem is the absence of a reference standard, in this case, the specific Indonesian National Standard (SNI) for ventilator products, getting the highest RPN score of 567. That is confirmed by other experts who work in certification bodies that Currently, Indonesia does not have it yet. Hence, the prototype built during the 2020 pandemic uses open-source references from research institutions (FKUI, 2020).

The subsequent finding that becomes the second priority is the availability of material needs, spare parts, and work tools with an RPN score of 416.7. The root of the problem that was successfully explored was the finding of non-standard components so that for each unit produced, different tunings and adjustments had to be done. The company confirmed the failure because the materials and parts they received were from research institutions without an independent purchasing process to find a better supply source.

The potential for performance failure, which is ranked third with an RPN score of 396, is related to the readiness of the operational scheme to face the Covid-19 pandemic emergency. The informant confirmed that the challenges faced during the pandemic were the limitation on the number of workers due to social distancing, difficulties in mobilizing to testing agencies, and logistical constraints on sensor components that still have to be imported from abroad. Potential failure in the subsequent RPN ranking is regarding teamwork cooperation, equipment operated by authorized personnel, approved work instructions and SOPs, customer satisfaction, information on work implementation for all employees, sharing information on production targets, and stable company financial performance condition, and the comfort of the working place. The availability of work guidelines is emphasized in Table 6 under several indicators, i.e., all equipment operated using approved instructions with an RPN score of 327.1 and is ranked sixth. The seventh and eighth ranks were also related to work instructions, with an RPN score of 299.9. Evaluation of the use of the method & SOP has an RPN score of 281.1.

5. Result and Discussion

5.1 Company Performance Evaluation Compare with Other Researches

This study presents two empirical studies, the first on assessing Baldrige variables in organizations using questionnaire data, which according to the literature, is a self-assessment. The second is to evaluate Baldrige performance indicators according to independent reviewers with selected sources. As such, it provides a deeper level of reliability and validity regarding assessment, perception, and reporting. The second important aspect of these studies is improving and improving the quality of performance in organizations that can be developed over time.

This research results obtained the highest Baldrige score on leadership performance, as shown in Table 5 (a) and (b). The lowest score is received on the Operational and Process performance variables. That is consistent with the results of previous research in the application of quality management in industry (Anastasiadou & Taraza, 2019; Fatima & Mahaboob, 2018; Mellat-Parast, 2015; Parast & Golmohammadi, 2019; Savov et al., 2017; Thompson & Blazey, 2017). This research found that the leadership factor is the primary driver of the quality performance of the organization. These results confirm the Baldrige concept that organization system is driven by leadership as well as senior staff, and this is the primary key to improving quality performance (Ahuja et al., 2019; Asif et al., 2019; Parast & Golmohammadi, 2019; Savov et al., 2017).

Table 5 (a) Performance criteria that needs to be improved

Priority	Based on Baldrige scoring
1st	Operational (criteria 6)
2nd	Measurement, analysis, and knowledge management (criteria 4)
3rd	Workforce (criteria 5)

Table 5 (b) Dominant Performance Criteria

Dominant	Criteria	Actual / Ideal score	(%)	Gap
The highest score	Leadership	58.00 / 120	48.33%	2.47 %
The lowest score	Operational	36.67 / 85	43.14%	-2.72 %

Table 6 below is compiled from various references related to the development of organizational performance and its significant factors. These essential factors affect organizational performance, either directly or indirectly, and positively encourage or hinder organizational performance improvement. The leadership factor is a significant factor affecting organizational performance, both positive and negative (Nandasinghe, 2020), (Parast & Golmohammadi, 2019), (Asif et al., 2019), (Ahuja et al., 2019), (Anastasiadou & Taraza, 2019), (Savov et al., 2017).

Table 6. Significant Factors for Organizational Performance in Previous Research

Description	Previous researches
Leadership factor	(Nandasinghe, 2020), (Parast & Golmohammadi, 2019), (Asif et al., 2019), (Ahuja et al., 2019), (Anastasiadou & Taraza, 2019), (Savov et al., 2017).
Training and sharing of knowledge and attention to employee intellectual property	(Kanapathipillai & Azam, 2020), (Ahmed et al., 2020), (Muwardi et al., 2020), (Mahmud et al., 2020), (Abdul Rauf et al., 2020), (Abbas et al., 2018), (Abualoush et al., 2018), (Chaudhry et al., 2017), (Puška et al., 2018)
Strategic Planning	(Kasushik & Guleria, 2020), (Chioke & Mbamalu, 2020), (Ahuja et al., 2019), (Anastasiadou & Taraza, 2019), (Dobrosavljević & Urošević, 2019)
External Organization Factor (social, politic, environment)	(Yap, 2020), (Ahlstrom et al., 2020), (Amarkhil, 2019)

One literature shows the importance of the causal relationship from the leadership factor to the information factor. The analysis is quantitatively demonstrated, proving that leadership has a vital role in information analysis and knowledge management variables. (Parast & Golmohammadi, 2019). Another study examined the relationship between leadership, quality of administration, quality of medical services, and patient satisfaction using the MBNQA criteria. Further research in hundreds of Pakistan hospitals investigated the effect of interventions on quality of medical service with relation to patient satisfaction and leadership. It obtained a positive relationship between leadership, administrative quality, medical quality, and patient satisfaction. In addition, administrative quality and medical quality were found as potential mediators in the relationship between leadership and customer satisfaction (Asif et al., 2019).

The second factor is by improving the internal work system of the organization, which is manifested by training actions, sharing knowledge between members of the organization and between departments so that the main objectives of the organization are achieved with the best collective performance and also job rotation (Sebt & Ghasemi, 2021), (Kanapathipillai & Azam, 2020), (Ahmed et al., 2020), (Muwardi et al., 2020), (Mahmud et al., 2020), (Abdul Rauf et al., 2020), (Abbas et al., 2018), (Abualoush et al., 2018), (Chaudhry et al., 2017), (Puška et al., 2018).

The third significant factor, according to the previous literature, is strategy and planning (Khan et al., 2021), (Kasushik & Guleria, 2020), (Chioke & Mbamalu, 2020), (Ahuja et al., 2019), (Anastasiadou & Taraza, 2019), (Dobrosavljević & Urošević, 2019), which in this research, it is included in the Baldrige variable number 2. However, this study did not find that variable is the dominant performance. However, strategic planning is still needed, especially the redesign of the roles and functions of each employee to adapt to the post-pandemic new normal conditions.

According to the literature, the fourth significant factor is the external influence of the organization, namely the social, environmental, or political policies imposed by the government. There are challenges in the form of Social Restrictions policies that limit the industry's movement both organizationally and in employee activities. Working conditions under pressure, restrictions on job access, and decreased employee motivation will affect organizational performance (S. A. Anggara et al., 2019). However, other research shows that managing the risks that may arise will improve the performance of the company organization (Najib et al., 2019).

The literature review also shows the importance of customer relationship management, leadership, communication, and strategic alignment as a very significant causal in implementing efficient continuous performance improvement. (Ahuja et al., 2019). As a comparison, researchers also reviewed research on evaluating organizational performance in education using the Baldrige criteria in Greece. The results of these studies prove that the main factor in their Tertiary Education System is leadership. The following variable that must be taken into account is Strategic Planning, which also has a significant effect on the successful implementation of quality (Anastasiadou & Taraza, 2019). The last article used as a reference shows that using a performance measurement system will affect organizational performance, especially helping organizations monitor performance, which ultimately leads to target achievement and gathering information and activity records that are useful for improving its performance. This system will affect various aspects of the organization, including financial and non-financial performance, employee behavior, and overall performance (Owais & Kiss, 2020).

5.2 Research Contribution to the Company

This research provides several contributions to the companies related to evaluating their performance, including leadership, strategic planning, knowledge management, customer handling, employment, operations, and production. First, this research evaluates the companies' performance using a Baldrige model, which is theoretically robust and has been widely applied in the business world. It is the first empirical performance evaluation to PT-EMB uses this kind of performance measurement. One of the critical implications of this finding is that the PT-EMB will use the Baldrige model as a self-assessment tool to improve the quality of performance further.

Table 7. List of performance indicator to be improved by PT-EMB

No	Performance variable	Performance indicator to be modified/improved	Indicator ID
1	Operational and process	Availability of materials, spare parts, and tools	29
		Preparation of operational schemes to deal with emergencies such as the Covid-19 pandemic	34
		Equipment operated by authorized personnel	32
		All equipment is operated using approved instructions	31
		Evaluate the use of methods and SOPs	33
2	Measurement, analysis, and knowledge management	Use of working procedures and instructions in operating tools	22
		Information and socialization of job task to all employees	20
3	Business results	Implementation of the national standard for ventilator product	41
		Customer satisfaction is met	36
		Production targets are met without defect	35
		Organizational financial condition is maintained	37
		Compliance with local industry regulations	40
4	Workforce	Teamwork enhancement	24

Previous research has used the Baldrige model to improve performance quality using cross-sectional surveys (Parast & Golmohammadi, 2019), and it usually follows up with SWOT analysis. Thus, the second contribution of our research is the novelty that brings up Baldrige indicator assessment via FMEA to produces suggestions for performance improvements on a priority scale. This is a contribution to academic theory as well that combines Baldrige with FMEA approach.

The third contribution of this research is to understand how to carry out comprehensive organizational performance measurements regardless of the business model and looking for loopholes to improve the quality of performance using the Baldrige approach. The improvement suggestions to the company are listed out relevant with each main criterion in Table 7.

One of the critical points of the discussion above is the absence of a specific Indonesian national standard (SNI) for the production of ventilators. Although this SNI is the government's responsibility through the National Standardization Agency for Indonesia, this does not escape its responsibility in ensuring the quality of its products. In general, the production process at this company has met the ISO-13485 quality standard (the quality standard for the medical device industry) except for the local ventilator production line, which specifically mass-produced prototypes made in Indonesia.

In addition, it is recommended that the PT-EMB involves the quality team from the planning stage, the purchasing process stage, and the material receiving stage. At the planning stage, selecting materials and determining specifications that guarantee quality should be considered. In the purchasing stage, the supplier selection must be reviewed and the technical quality specifications offered by the supplier. When receiving goods, the quality team must verify all materials are per the desired quality.

5.3 Research Limitation

This study has limitations related to social and activity restrictions due to the pandemic in the company, which causes questionnaire data collection, interviews, and discussions to be carried out in stages repeatedly—some using a paper questionnaire form and some using an online application. The same thing was done when FGD discussions with experts were conducted online using the video call facility and the online google-form application. The time limitation possessed by the five experts can be overcome by partially discussing several stages until all the results are collected, which can be made a consensus with the confirmation of the experts as a resource.

Organizational performance appraisal using the Baldrige variable in this company has never been carried out other than a performance appraisal for employees as a requirement for calculating the annual bonus and ISO13485 assessment for administrative production areas. Thus, the result cannot be compared to the previous comprehensive company performance evaluation. Other industries in Indonesia that use the Baldrige variable are only government-owned companies, hospitals, and educational institutions; hence, benchmarking cannot be carried out.

The performance evaluation was in the Cov-19 pandemic period so that company activities were only prioritized for the production of equipment for Covid-19 handling, which was carried out urgently, i.e., oxygen generators and local prototype ventilators, and might be different from activities in normal conditions either before or after the pandemic.

6. Conclusion and Suggestion

6.1 Conclusion

The results showed that the performance of this company, when analyzed using the Baldrige variable, was at the early improvement level of achievement, with the best value performance in the leadership variable and the lowest value performance in the operational variable. It is in line with the expert's evaluation that the priority performance should be improved is the Operational variables. Apart from these variables, other variables also show weak performance indicator items, namely in the knowledge management variable, performance analysis, and measurement and outcome variables. Weak performance in the labor variable is only found in the indicator of co-worker cooperation.

This study produces solutions to improve company performance in the order of priority. In practical terms, the performance items that involve the internal company will be easily corrected. What will be difficult to implement is the availability of national standards for ventilator products. Until the time this research was compiled has not been issued by the National Standardization Agency for Indonesia.

6.2 Suggestion for Future Research

- Evaluating organizational performance using the Baldrige variable for manufacturing electro-medical devices can be a role model for similar industries, particularly in Indonesia and South East Asia. The obstacles encountered can be used as lessons learned by other researchers.
- Organizational evaluation using the Baldrige model combined with FMEA was not found in previous literature. Thus, further research is expected to be followed that will strengthen the use of these approaches.

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ASSESSING COUNTRY PERFORMANCES DURING THE COVID-19 PANDEMIC: A STANDARD DEVIATION BASED RANGE OF VALUE METHOD

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Abstract: *In this paper, we compare the pandemic management performance of 22 countries that belong to the middle-high income class based on criteria including the pandemic data, population characteristics, and health system capacity. The management of the COVID-19 pandemic requires considering many and often conflicting aspects at the same time which necessitates an MCDM approach. We use a standard deviation (SDV) based range of value (ROV) method which coincides with the black-box nature of the disease. The weights obtained from the SDV method reveal that the number of COVID-19 deaths, current health expenditure, and deaths due to cardiovascular diseases are the most important criteria. The ROV method indicates that most Asian countries are ranked in higher positions due to their strong healthcare systems and quick implementation of social distancing rules. The lowest performances belong to Bulgaria, Montenegro, and Bosnia and Herzegovina. They have experienced an elevated number of deaths due to having an elderly population and inefficient usage of healthcare resources. We also show that extreme poverty is an important determinant of country performance. In countries where poverty is higher, as the case with Indonesia, implementing the social distancing rules becomes almost impossible which affects the overall country performance significantly.*

Keywords: *COVID-19 pandemic, ROV method, SDV method, MCDM, middle-high income countries*

1. Introduction

It has been more than a year since the World Health Organization first declared the new Coronavirus disease (COVID-19) was a pandemic. After one year and several

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waves, COVID-19 caused 113,051,293 cases and more than 2,500,000 deaths[1]. Although we have learned many things about the disease, and several COVID-19 vaccines have been developed, the importance of the studies to clarify the effects of the disease has not been reduced. Any research that helps reduce the burden on the healthcare system and flatten the spread rate is still valuable. In this study, we aim to compare the performance of a relatively homogenous group of countries in their fight against the COVID-19 during the ongoing pandemic. More specifically, we rank the pandemic management performance of 22 countries that belong to the middle-high income class according to the World Bank classifications based on many criteria, namely pandemic data, population characteristics, and health system capacity. The existence of various factors and often conflicting criteria at the same time makes the issue of ranking country performances as a Multi-Criteria Decision Making (MCDM) problem. For this aim, we use a combination of two MCDM techniques, namely the standard deviation approach (SDV) for the criteria weights and range of value (ROV) method in order to compare country performances against COVID-19.

Regarding the aim of our study, we note two related fields of research: The first field investigates how well countries all over the world cope with the pandemic. Adabavazeh et al. (2020) note that benchmarking is essential for the healthcare systems to improve their working process and to be prepared for future public health crises. Hence, it is natural to observe a specific line of research in the COVID-19 literature. These studies concentrate on the performance rankings of different countries with various methodologies. Jamison et al. (2020) examine the performances of 35 countries according to the doubling times of confirmed cases and deaths at three different points in time during the beginning of the pandemic. They demonstrate that although the variation among the cross-country performances is modest initially, the difference between countries gets wider between later days. Aydin and Yurdakul (2020) rank the country performances against COVID-19 by using an extension of data envelopment analysis (DEA) and different machine learning algorithms. They aim to show which factors affect the number of confirmed cases and deaths the most. Maroko et al. (2020) aim to compare the neighborhoods in New York City, the USA, in terms of population characteristics. Olivia et al. (2020) evaluate the current pandemic management of Indonesia by comparing its performance with Lombardy (Italy) and New York (the USA) as well as other Asian countries.

The second group of related works is the ones that apply different decision-making approaches to COVID-19 studies. Among those studies, Shirazi et al., (2020) rank the performance of hospitals in Iran and their capability to meet patients' needs during the pandemic by using FAHP – PROMETHEE methods. Samanlioglu and Kaya (2020) evaluate the intervention strategies that countries have adopted to flatten the epidemiological curve by using the hesitant fuzzy AHP method. Kayapinar Kaya (2020) assesses the impact of COVID-19 on the sustainable development levels of the OECD countries by employing the MAIRCA technique and compares the findings with two other MCDM models, i.e. MABAC and WASPAS. Yiğit (2020) analyzed the performance of OECD countries during the current pandemic by employing the TOPSIS approach. In this study, the healthcare system performance proxies, such as health expenditures, the number of medical staff, and COVID-19 related indicators are employed as criteria,

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[1] Data from: https://www.worldometers.info/coronavirus/ Access Date: 24.02.2021

while 36 OECD countries constitute the alternatives. This study reveals that Asian Pacific countries are the more successful ones in this struggle whereas the European and Middle Eastern countries demonstrate bad performance.

Determining a good country performance against COVID-19 requires considering many types of criteria at the same time. Population characteristics, such as age, accompanying chronic diseases, the level of poverty are important factors in this struggle. Still, the biggest burden is on the healthcare system components. Among the primary determinants of pandemic management success, we can observe the timely detection of the newly infected ones, providing good healthcare, and limiting the number of deaths. The existence of various and conflicting criteria creates a need for MCDM techniques. Hence, we use two MCDM techniques combinedly, namely the SDV and the ROV approaches, to determine the rankings of the countries. To the extent of our knowledge, this is the first study that applies an SDV based ROV method to analyze the country's performances in the battle against the current pandemic. By doing so, we aim to contribute to both lines of the above-mentioned researches.

MCDM is a very common methodology to rank the decision options according to a group of criteria (Hajkowicz & Higgins, 2008). This particular nature allows us to compare the country's performances in the fight against COVID-19. In this sense, the aim of our study is related to the paper by Yiğit (2020). Here, we must mention the significant differences between this paper and ours. Yiğit (2020) considers the early phases of the pandemic with only healthcare-related criteria. However, COVID-19 created a very fast-changing environment in all areas. Therefore, re-evaluating the performance of the countries and showing the differences between the ongoing situation and the early stages even for a short period of time still adds to the efforts that aim to decrease its negative effects. It is also known that the struggle against the COVID-19 does not only depend on healthcare system, but also the characteristics of vulnerable population. These criteria must be added into country comparisons. Unlike Yiğit (2020), we consider population-related criteria such as the prevalence of chronic diseases and the percentage of elderly population. Besides, we focus on a different and more homogenous group of countries. It is natural to draw different conclusions from this comparison relative to a more heterogeneous country group. Last, we use a different combination of MCDM techniques. As a result, we believe that benchmarking the countries in the first year of the pandemic is still important to suggest policy changes for the worst-performing ones.

Bedford et al. (2020) indicate that the struggle against the COVID-19 pandemic is harder for the countries in the low and middle-income groups than the higher-income group countries. The literature, however, mostly concentrates on the USA and European countries where the pandemic hit hard initially. The burden of the pandemic on the healthcare workers and units is devastating even for the better prepared higher-income countries. De Nardo et al. (2020) state that the situation is, even more, overwhelming for low- and middle-income countries where the healthcare facilities are limited and mobility restrictions are difficult to be applied. In this study, we consider the middle-high income group countries, a less examined sample that also includes the origin of the pandemic, i.e. mainland China. We believe that such a comparison will help more disadvantaged countries to be prepared for future infection spreads, to decrease the economic and social effects of pandemics, and to allocate healthcare resources efficiently.

Our findings reveal that Asian countries like Thailand, mainland China and Malaysia produce better rankings in this comparison. These countries are more experienced in the management of infectious diseases due to previous epidemics, i.e. SARS. However, Bosnia and Herzegovina, Bulgaria, and Montenegro have more disadvantaged rankings. Their relative low performance can be attributed to the higher levels of the elderly population and their related co-morbidities as well as the inefficient management of the existing healthcare resources.

We clearly show that countries that are successful in pandemic management have stronger healthcare systems and they have been more prepared for such a disaster. Countries that are ranked in the lower positions either have limited capacity or cannot manage their resources efficiently. Delaying to take necessary social distancing precautions is likely to increase the number of COVID-19 deaths and lowers the country's performance.

The success in pandemic management also depends on population characteristics. Having an elderly population increases the overall burden in the healthcare system because it increases the requirement for long term attention. In distressing times, like the COVID-19 pandemic, along with the co-morbidities, countries experience many difficulties to manage the crisis, no matter how high the level of the current expenditure is. In countries, where poverty is higher, implementing the social distancing rules becomes almost impossible. With that limited access to clean water and other hygiene products, the number of cases and deaths rapidly escalates. Authorities must adopt policies regarding elderly care and people living below the poverty line.

This paper continues with the literature review section that summarizes the related lines of research. The data and methodology section explains the details of the data and the selected MCDM method. Section 4 presents the findings and the policy discussions based on these results. We compare the robustness of our results in Section 5. The last section concludes.

2. Related Literature

Since the beginning of the COVID-19 pandemic, there has been vast literature discussing its effects in every aspect of our lives. Besides discussing the impact of the pandemic on our social and professional lives, many studies examine the effectiveness of different precautions to deal with the COVID-19. In this paper, we aim to compare the performances of countries in the battle against the current pandemic by using a combination of two MCDM techniques. Therefore, in this literature review we specifically focus on the two lines of research: First, we look at the literature that investigates how well countries all over the world cope with the pandemic. In this group, Jamison et al. (2020); Aydin and Yurdakul (2020); Adabavazeh et al. (2020) are highlighted. Second, we examine how different decision-making techniques are used in the COVID-19 studies. In the second group, the studies by De Nardo et al. (2020); Shirazi, et al. (2020); Yiğit (2020), and Kayapinar Kaya (2020) are stand out among the others.

The study by Jamison et al. (2020) is one of the first ones that investigate the county performances against COVID-19. They compare the performance of 35 countries with different characteristics in the early times of the pandemic depending on the doubling times of new cases and COVID-19 related deaths per 1,000,000 population. They aim to show which policy choices of different governments provide better health and economic results. Their results indicate that in the less populated countries, the pandemic started with more severity, but in time, the more populated countries were affected more. Brazil and India have always shown a bad performance in terms of controlling the pandemic. The cases in Iran and Indonesia doubled more quickly in the later comparisons than the initial times. Turkey showed a good performance and its ranking is above the average of 35 countries in terms of both new cases and deaths.

Aydin and Yurdakul (2020) and Adabavazeh et al (2020) employ the DEA method in the analysis of country efficiency. More specifically, Aydin and Yurdakul (2020) develop a novel three-stage DEA model called WSIDEA to identify country performances based on the number of COVID-19 cases and deaths and other population and economic characteristics. They cluster 142 countries into 3 groups and obtain their efficiencies according to the WSIDEA method. The factors that affect country efficiency levels are examined with decision trees and random forest algorithms. Adabavazeh, et al. (2020), on the other hand, employ the traditional DEA method to analyze the efficiency of healthcare units in 71 different countries where population, GDP per capita, day of infection, and the total number of cases are inputs and the number of total recovered patients and total deaths are outputs. They employ a BCC type output-oriented DEA model. Among them, 16 healthcare units including those located in mainland China and Iran are found efficient.

The second line of research applies different decision-making tools in COVID-19 studies, such as MCDM techniques, fuzzy sets, and artificial intelligence. These applications include many different fields, ranging from the prediction of future risks and the effectiveness of the non-healthcare precautions to medicine selection and hospital admissions.

Among the examples of fuzzy sets and artificial intelligence applications in the struggle against COVID-19, the following studies can be examined: Pal et al. (2020) benefit from artificial intelligence to predict long term country-specific risks and to group them as high-risk, low-risk, and recovering countries. Majumder et al. (2020) develop a decision-making tool based on TOPSIS. They try to identify the possible COVID-19 patients depending on their linguistic information in order to help early detection of newly infected people and to send them self-isolation or home quarantine. They replace the Euclidian distance computation of proximity to ideal solutions with supremum distance. Next, they apply an artificial neural network approach to provide real-time monitoring for death values. Si et al. (2021) propose a decision-making approach for appropriate medicine selection by employing fuzzy sets and grey relational analysis. Mishra et al. (2021), following Si et al. (2021), rank alternative medical treatments to apply for the mild cases of Covid-19. They employ an ARAS framework with hesitant fuzzy information. The attribute weights are obtained through the HF-divergence measure. Khatua et al. (2020) employ granular differentiability based fuzzy SEIAHRD model to control the current pandemic in India. Their results indicate that an optimal pandemic control requires more testing to detect the infections, hospital quarantine, and long-term partial lockdowns in the country.

The following group of studies constitutes examples for the application of MCDM techniques to the COVID-19 studies. Sayan et al. (2020) employ two different MCDM techniques, namely fuzzy PROMETHEE and fuzzy TOPSIS to rank seven diagnostic alternatives of COVID-19 based on different criteria such as test sensitivity, cost, usability, false result rates, accessibility, equipment.

Samanlioglu and Kaya (2020) assess the non-healthcare precautions, including mobility and border restrictions, lockdowns, school closures, declaration of a state of emergency in the struggle against the current pandemic by employing a hesitant fuzzy AHP method. De Nardo et al. (2020) use PAPRIKA as an MCDM technique to detect and prioritize the hospital admissions of COVID-19 patients with the potential of quick clinical deterioration in Italy. The criteria weights are based on a survey applied to the experts who deal actively with COVID-19 patients. The PAPRIKA method compares all combinations of criteria pairs. Shirazi, et al. (2020) examine patient satisfaction under normal terms and under times of health crisis, such as the current pandemic. To do so, they rate the hospitals in Iran and determine the factors of patient satisfaction by using a combination of the Fuzzy AHP-PROMETHEE approach. Kayapinar Kaya (2020) assesses the sustainable development performance of OECD countries before and during the COVID-19 pandemic by using MAIRCA as the main analysis method. She compared the rankings of MAIRCA with two other MCDM techniques namely WASPAS and MABAC. She showed that although the pandemic affects negatively all countries' sustainable development levels, developing countries are more negatively impacted. Sangiorgio and Parisi (2020) develop an index to forecast the contagion risk under different mobility scenarios in urban areas to support the decision-making process of local authorities. To do so, they collect data from 257 urban areas in Italy and they design the problem as AHP based multi-criteria approach. Next, they calibrate the model by using the GRG-optimization method and compared the results with an analysis based on the Artificial Neural Networks.

Yiğit (2020) compares the performance of 36 OECD countries by using the TOPSIS method in their struggle against the current disease. She considers the countries as alternatives to rank and employs healthcare indicators as equally weighted criteria. These criteria include the number of COVID-19 patients and deaths, healthcare system expenditures by governments, and current healthcare capacities, such as hospital beds and the number of physicians. She states that although one may observe a high correlation between healthcare expenditures and life expectancy, some countries do not comply with this anticipation. For example, Portugal, Spain, and Israel are among the countries with high life expectancy but their healthcare expenditures are lower than the OECD average. As a result, as indicated by Yiğit (2020), in a worldwide healthcare crisis, this situation leads to different performance rankings. The findings of Yiğit (2020) suggest that Asian countries in the OECD sample react more proactively to the ongoing pandemic relative to European countries and the USA.

The studies applying several decision-making tools on COVID-19 are summarized below in Table 1.

Our study aims to combine these two lines of research mentioned above. In particular, we aim to rank the countries in the middle-high income group based on their performances against the current pandemic while employing MCDM techniques. Although these techniques provide transparent and consistent comparisons as noted by De Nardo et al. (2020), the studies applying MCDM to the country performances are rather scarce. In this sense, our aim coincides most with the study by Yiğit (2020).

Table 1. The Studies Applied Decision-Making Tools in the Struggle Against COVID-19

Authors	The Aim of the Paper	The Decision-Making Tool
Yiğit (2020)	To compare the country performances based on the healthcare criteria in the battle against the current pandemic	TOPSIS
Sayan et al. (2020)	To compare the COVID-19 diagnostic tool alternatives	Fuzzy PROMETHEE and Fuzzy TOPSIS
Samanlioglu and Kaya (2020)	To rank the precautions other than the healthcare system measures against COVID-19	Hesitant Fuzzy AHP
De Nardo et al. (2020)	To prioritize the hospital admissions of not currently but potentially urgent patients.	PAPRIKA
Kayapinar Kaya (2020)	To rank the sustainable development levels of countries before and during the COVID-19 pandemic	MAIRCA results compared with WASPAS and MABAC
Shirazi, et al. (2020)	To rate the hospitals in Iran according to the patient satisfaction under normal and pandemic conditions	A combination of Fuzzy AHP-PROMETHEE
Sangiorgio and Parisi (2020)	To predict the contagion risk of COVID-19 based on different mobility restriction scenarios	AHP based multi-criteria approach and GRG-optimization method. The results are compared with those obtained from ANN.
Khatua et al. (2020)	To find the requirements for an optimal pandemic control in India	Granular differentiability based fuzzy SEIAHRD
Majumder et al. (2020)	To detect the potential COVID-19 patients based on their verbal information	Supremum distance TOPSIS method combined with ANN
Pal et al. (2020)	To determine the long term COVID-19 risks of a country	Artificial Intelligence
Si et al. (2021)	To choose appropriate medicine to treat COVID-19 patients	Fuzzy sets and grey relational analysis
Mishra et al. (2021)	To rank medical treatment alternatives of mild COVID-19 patients	ARAS framework with hesitant fuzzy information

However, there are important differences between these two papers. We consider a more homogenous and less investigated sample of countries than Yiğit (2020). Benchmarking of countries is more intuitive when the sample becomes less heterogeneous. In addition to the healthcare indicators employed in Yiğit (2020), we also consider population-based criteria, such as the elderly ratio, extreme poverty, and the existence of co-morbidities in our analysis. These criteria are also known as important determinants of the number of COVID-19 deaths and cases. Therefore, the performance comparison of countries in this battle must consider these criteria as well. The criteria ranking is done based on an objective weighting method called the SDV approach. The country comparisons are realized based on the ROV method. We believe that our selection of criteria weighting and alternative ranking methods overlap the black-box nature of the ongoing pandemic. Last, we employ a later time period for the ongoing pandemic to compare the performances. Such a comparison in this fast-changing environment is very valuable.

3. Data and Methodology

This study collects data for 22 countries that are classified as middle-high income group by the World Bank[2]. These countries are Albania, Argentina, Armenia, Bosnia and Herzegovina, Brazil, Bulgaria, mainland China, Columbia, Costa Rica, Dominican Republic, Ecuador, Georgia, Indonesia, Iran, Kazakhstan, Malaysia, Mexico, Montenegro, Paraguay, Russia, Thailand, and Turkey. As of the date of the analysis, this sample covers 25% of the total cases and 32% of the COVID-19 related deaths worldwide. These countries create a rather homogeneous group to provide a ranking for their performances and also contain mainland China, which is the origin of the pandemic and the most discussed country for its crisis management methods. The study begins with the identification of performance criteria and application of the SDV method to weight them. Next, the ROV method will be applied as the main analysis method, where the results are compared TOPSIS and EDAS approaches. For clarity, we show the general framework of our work in Figure 1.

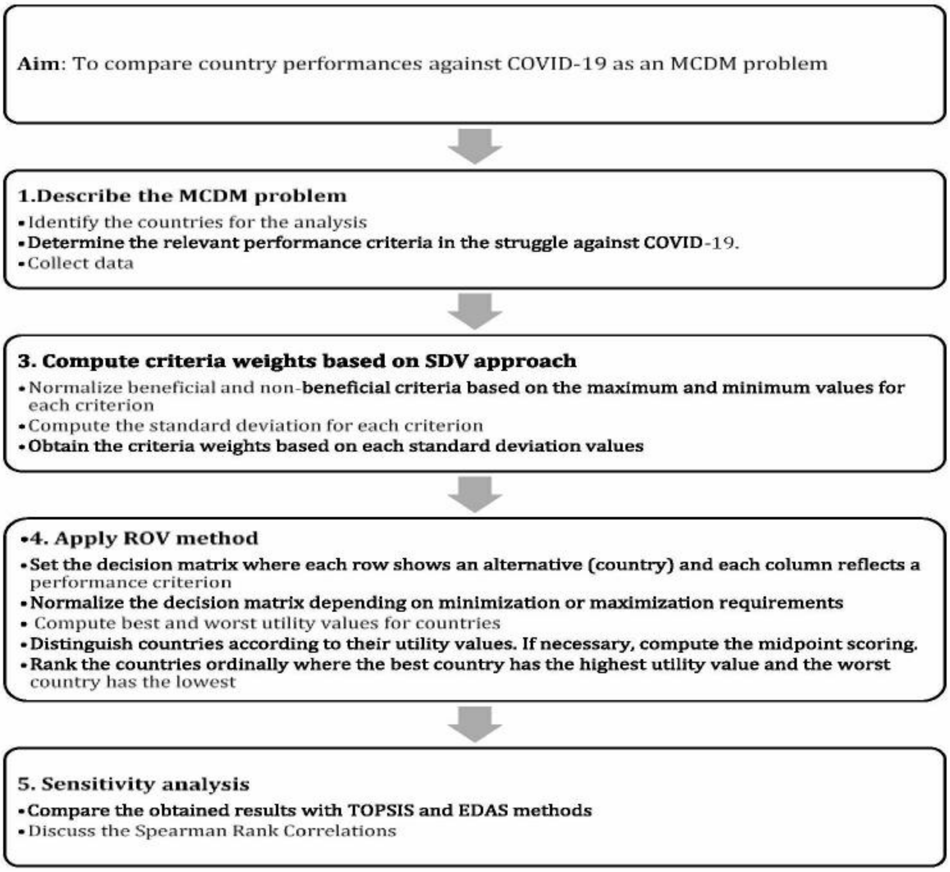

Figure 1. General working diagram of the study

[2] The World Bank, https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups, Access Date: 24.02.2020

For the comparisons, 12 evaluation criteria have been selected based on the studies by Adabavazeh et al. (2020), Aydin and Yurdakul (2020), George et al. (2020), and Khafaie and Rahim (2020). Those criteria, their codes, and the sources from which the data is obtained are provided in Table 2.

Table 2. The Criteria used in the Analyses, Their Codes and Data Sources

Criteria	Codes	Definition	Data Source
Total Cases	C1	The number of patients that have positive PCR tests per 100.000 people	https://www.worldometers.info/coronavirus (Access Date: 20.01.2021)
Total Deaths	C2	Total number of deaths due to COVID-19 per 100.000 people	https://www.worldometers.info/coronavirus (Access Date: 20.01.2021)
Extreme Poverty	C3	The percentage of the population living less than daily $1.90	https://ourworldindata.org (Access Date: 20.01.2021)
Cardiovascular Death Rate	C4	The annual number of deaths due to cardiovascular diseases per 100.000 people in a given country.	https://ourworldindata.org (Access Date: 20.01.2021)
Diabetes Prevalence	C5	The rate of people aged between 20 and 79 with type 1 and type 2 diabetes	https://ourworldindata.org (Access Date: 20.01.2021)
Female Smokers	C6	The number of women who smoke in a given country.	https://ourworldindata.org (Access Date: 20.01.2021)
Population Aged 65 +	C7	The rate of people aged 65 and above to the total population in a given country.	The World Bank Database (2019)
Male Smokers	C8	The number of men who smoke in a given country.	https://ourworldindata.org (Access Date: 20.01.2021)
Current Health Expenditure	C9	The amount of health expenditures as a percentage of the GDP of a given country.	The World Bank Database (2018)
Total Recovered	C10	The number of patients recovered from COVID-19 infection per 100.000 people.	https://www.worldometers.info/coronavirus (Access Date: 20.01.2021)
Hospital Beds Per Thousand	C11	The number of hospital beds per 1000 people in a given country.	https://ourworldindata.org (Access Date: 20.01.2021)
Total Tests	C12	The number of total PCR tests to diagnose COVID-19 infections per 100.000 people.	https://www.worldometers.info/coronavirus (Access Date: 20.01.2021)

3.1. Standard Deviation Method

The standard deviation method is used to weight the criteria in this analysis. This method is developed by Diakoulaki et al. (1995) and the weights are determined according to the standard deviations of criteria. This is an objective weighting method in which decision-makers do not influence establishing the relative importance of criteria. This method gives lower weights to an attribute as long as the attribute has similar values in different alternatives. As a result, the contrasting attribute in the alternatives becomes much highlighted (Diakoulaki et al., 1995; Hassan et al., 2015). Diakoulaki et al. (1995) indicate that when the criteria are interdependent, the results might be misleading. However, removing some of these interdependent criteria might cause a loss of important information as well. In this case, using the standard deviation method in the weight determination might be a solution. This feature of the standard deviation method becomes more important when the nature of the COVID-19 pandemic is considered. As an example, the criteria in Table 2 include total confirmed cases, total tests, and deaths. Naturally, as more testing is performed, more cases will be confirmed and more COVID-19 deaths will be detected. However, the omission of any of these criteria will result in a loss of information.

While obtaining the weights into the standard deviation method, first, a normalization process is applied through Eq. (1) and Eq. (2) to provide a common and measurable basis for criteria that differ in scale and units (Diakoulaki et al., 1995; El-Santawy & Ahmed, 2012):

$$x'_{ij} = \frac{x_{ij} - \min_{i=1}^{m}(x_{ij})}{\max_{i=1}^{m}(x_{ij}) - \min_{i=1}^{m}(x_{ij})} \quad \text{i= 1,2,...,m; j = 1,2,... ,n (for beneficial)} \tag{1}$$

$$x'_{ij} = \frac{\max_{i=1}^{m}(x_{ij}) - x_{ij}}{\max_{i=1}^{m}(x_{ij}) - \min_{i=1}^{m}(x_{ij})} \quad \text{i=1,2,...,m; j=1,2,...,n (for non-beneficial)} \tag{2}$$

There are m alternatives and n criteria. Here, x_{ij} is the raw score of i^{th} alternative for criterion *j*. $(x')_{mxn}$ is the matrix after the normalization process, while max x_{ij} and min x_{ij} are the maximum and minimum values of x_{ij} respectively. The standard deviation for each criterion is computed with the aid of Eq. (3).

$$SDV_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(x'_{ij} - \bar{x}'_j)^2} \tag{3}$$

$\bar{x}'_j$ is the average of the values of the j^{th} criterion after the normalization process, and j=1,2,...,n.

After obtaining standard deviation values, the weightings of criteria are computed by using Eq. (4).

$$w_j = \frac{SDV_j}{\sum_{j=1}^{n} SDV_j} \quad \text{j = 1,2,..., n} \tag{4}$$

3.2. Range of Value (ROV) Method

ROV approach is developed by Yakowitz and Szidarovxzky (1993). Hajkowicz and Higgins (2008) state that this method is especially beneficial when it is not possible or meaningful to provide quantitative weights. After one year of the pandemic, COVID-19 still protects its black box nature in many aspects. Therefore, instead of assigning quantitative weights, we find the ROV method more suitable to assess the country's performances during the pandemic. To the extent of our knowledge, this is to first paper that combines the ROV approach with the standard deviation method in both MCDM and COVID-19 literature.

ROV method basically computes the best and worst utility values for each alternative (Hajkowicz & Higgins, 2008). To calculate those values, the utility function is maximized and minimized, respectively. As a result, the performance rankings of alternatives are obtained.

The procedure for the application of the ROV method is simple which constitutes another strong point for this approach. The application steps are as follows (Madić et al., 2016):

Step 1: The relevant criteria to assess the existing alternatives are set.

Step 2: The decision matrix is formed. In this matrix, each row represents an alternative whereas each column reflects a criterion.

Step 3: The decision matrix is normalized at this stage. For beneficial criteria, where maximization is applied, the normalization is done by using Eq. (5) below:

$$\overline{x}_{ij} = \frac{x_{ij} - \min_{i=1}^{m}(x_{ij})}{\max_{i=1}^{m}(x_{ij}) - \min_{i=1}^{m}(x_{ij})} \quad (5)$$

For the non-beneficial criteria, however, where minimization is applied, the normalization is done by using Eq. (6) below:

$$\overline{x}_{ij} = \frac{\max_{i=1}^{m}(x_{ij}) - x_{ij}}{\max_{i=1}^{m}(x_{ij}) - \min_{i=1}^{m}(x_{ij})} \quad (6)$$

In both Eq (5) and (6), x_{ij} is the raw score of i^{th} alternative for criterion *j*. There are m alternatives. max x_{ij} and min x_{ij} are the maximum and minimum values of x_{ij}, and the $\overline{x}_{ij}$ is the normalized values.

Step 4: For each alternative, the best and worst utility values are computed as in Eq. (7) and (8).

$$\text{Max: } u_i^{+} = \sum_{j=1}^{n} \overline{x}_{ij} * w_j \quad (7)$$

$$\text{Min: } u_i^{-} = \sum_{j=1}^{n} \overline{x}_{ij} * w_j \quad (8)$$

Where u_i^{+} *and* u_i^{-} represent utility values and w_j reflects the criterion weight. The summation of the criterion weights must be equal to 1, and $w_j \geq 0$.

When u_i-≥u_i'+, the i^{th} alternative shows a better performance than the alternative *i'* without looking at the quantitative weights. If this basis is not sufficient to distinguish the alternatives, a midpoint scoring (u_i) can be used to allow the following ranking as such:

$$u_i = \frac{u_i^{-} + u_i^{+}}{2} \quad (9)$$

Step 5: In this last step, the alternatives are ordinally ranked based on their u_i values. The best alternative has the highest u_i, whereas the worst one has the lowest u_i.

4. Findings

Following the above procedure, the criteria that are presented in Table 2 are first weighted by using the standard deviation method. Next, the decision matrix is formed. Here, C1,…., C8 represent non-beneficial criteria to be minimized, while C9, C10, C11, and C12 are beneficial criteria, to be maximized. The decision matrix can be seen in Table 3.

Table 3. The Initial Decision Matrix

Countries	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Albania	2381.8	44.8	1.1	304.2	10.1	7.1	14.2	51.2	5.3	1470.4	2.9	11105.5
Argentina	4021.9	101.9	0.6	191.0	5.5	16.2	11.2	27.7	9.6	3591.0	5.0	12677.7
Armenia	5567.6	101.3	1.8	341.0	7.1	1.5	11.5	52.1	10.0	5201.8	4.2	21246.1
Bosnia and Herzegovina	3577.1	135.8	0.2	329.6	10.1	30.2	17.2	47.7	8.9	2698.4	3.5	17304.2
Brazil	4033.0	99.6	3.4	178.0	8.1	10.1	9.3	17.9	9.5	3584.2	2.2	13551.3
Bulgaria	3044.5	122.7	1.5	424.7	5.8	30.1	21.3	44.4	7.3	2510.0	7.5	18543.8
Mainland China	7.0	0.3	0.7	261.9	9.7	1.9	11.5	48.4	5.4	5.8	4.3	11447.2
Colombia	3820.3	97.3	4.5	124.2	7.4	4.7	8.8	13.5	7.6	3548.2	1.7	18555.9
Costa Rica	3685.2	48.6	1.3	138.0	8.8	6.4	9.9	17.4	7.6	2870.2	1.1	11012.0
Dominican Republic	1815.5	22.7	1.6	266.7	8.2	8.5	7.3	19.1	5.7	1356.5	1.6	9065.9
Ecuador	1333.3	82.4	3.6	140.4	5.6	2.0	7.4	12.3	8.1	1147.3	1.5	4742.1
Georgia	6663.6	79.5	4.2	496.2	7.1	5.3	15.1	55.5	7.1	6368.2	2.6	54798.1
Indonesia	338.8	9.7	5.7	342.9	6.3	2.8	6.1	76.1	2.9	282.1	1.0	3138.1
Iran	1611.5	68.6	0.2	270.3	9.6	0.8	6.4	21.1	8.7	1372.2	1.5	10413.8
Kazakhstan	1171.8	15.6	0.1	466.8	7.1	7.0	7.7	43.1	2.9	839.3	6.7	32097.7
Malaysia	506.2	1.8	0.1	260.9	16.7	1.0	6.9	42.4	3.8	399.5	1.9	13036.4
Mexico	1292.9	110.7	2.5	152.8	13.1	6.9	7.4	21.4	5.4	981.2	1.4	3284.4
Montenegro	8969.5	119.9	1.0	387.3	10.1	44.0	15.4	47.9	8.4	7592.0	3.9	34205.6
Paraguay	1740.1	35.7	1.7	199.1	8.3	5.0	6.6	21.6	6.7	1420.7	1.3	8769.1
Russia	2460.8	45.0	0.1	431.3	6.2	23.4	15.1	58.3	5.3	2096.8	8.1	67602.4
Thailand	18.0	0.1	0.1	109.9	7.0	1.9	12.4	38.8	3.8	13.8	2.1	1749.1
Turkey	2868.2	28.9	0.2	171.3	12.1	14.1	8.7	41.1	4.1	2737.5	2.8	33402.3

The next step is to normalize each element in the decision matrix. This process is done according to Eq. (1) for beneficial criteria and according to Eq. (2) for non-beneficial criteria. The normalized decision matrix is presented in Table 4.

Table 4. Normalized Decision Matrix

	Criteria											
Countries	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**
Albania	0.74	0.67	0.82	0.50	0.59	0.85	0.46	0.39	0.33	0.19	0.26	0.14
Argentina	0.55	0.25	0.91	0.79	1.00	0.64	0.66	0.76	0.94	0.47	0.56	0.17
Armenia	0.38	0.25	0.70	0.40	0.86	0.98	0.64	0.38	1.00	0.68	0.45	0.30
Bosnia and Herzegovina	0.60	0.00	0.98	0.43	0.59	0.32	0.27	0.45	0.84	0.35	0.35	0.24
Brazil	0.55	0.27	0.41	0.82	0.77	0.78	0.79	0.91	0.93	0.47	0.17	0.18
Bulgaria	0.66	0.10	0.75	0.19	0.97	0.32	0.00	0.50	0.63	0.33	0.91	0.26
Mainland China	1.00	1.00	0.89	0.61	0.62	0.97	0.64	0.43	0.35	0.00	0.47	0.15
Colombia	0.57	0.28	0.21	0.96	0.83	0.91	0.82	0.98	0.67	0.47	0.10	0.26
Costa Rica	0.59	0.64	0.79	0.93	0.71	0.87	0.75	0.92	0.66	0.38	0.01	0.14
Dominican Republic	0.80	0.83	0.73	0.59	0.76	0.82	0.92	0.89	0.40	0.18	0.08	0.11
Ecuador	0.85	0.39	0.38	0.92	1.00	0.97	0.91	1.00	0.74	0.15	0.07	0.05
Georgia	0.26	0.42	0.27	0.00	0.86	0.90	0.41	0.32	0.59	0.84	0.22	0.81
Indonesia	0.96	0.93	0.00	0.40	0.93	0.95	1.00	0.00	0.00	0.04	0.00	0.02
Iran	0.82	0.50	0.98	0.58	0.64	1.00	0.98	0.86	0.81	0.18	0.07	0.13
Kazakhstan	0.87	0.89	1.00	0.08	0.86	0.86	0.89	0.52	0.01	0.11	0.81	0.46
Malaysia	0.94	0.99	1.00	0.61	0.00	1.00	0.94	0.53	0.12	0.05	0.12	0.17
Mexico	0.86	0.19	0.57	0.89	0.33	0.86	0.91	0.86	0.35	0.13	0.05	0.02
Montenegro	0.00	0.12	0.84	0.28	0.59	0.00	0.39	0.44	0.78	1.00	0.40	0.49
Paraguay	0.81	0.74	0.71	0.77	0.75	0.90	0.96	0.85	0.53	0.19	0.04	0.11
Russia	0.73	0.67	1.00	0.17	0.94	0.48	0.41	0.28	0.34	0.28	1.00	1.00
Thailand	1.00	1.00	1.00	1.00	0.86	0.97	0.58	0.58	0.13	0.00	0.15	0.00
Turkey	0.68	0.79	0.98	0.84	0.41	0.69	0.82	0.55	0.18	0.36	0.25	0.48

In the last step of this method, the standard deviation of each performance criterion and its relevant weight is computed by using Eq. (3) and Eq. (4). The results are shown in Table 5.

Table 5. Standard Deviations and Criterion Weights

	Total Cases (C1)	Total Deaths (C2)	Extreme Poverty (C3)	Cardiovascular Death Rate (C4)	Diabetes Prevalence (C5)	Female Smokers (C6)	Aged 65 + (C7)	Male Smokers (C8)	Current Health Expenditures (C9)	Total Recovered (C10)	Hospital Beds Per 1000 (C11)	Total Tests (C12)
SDV_j	0.25	0.33	0.30	0.31	0.24	0.27	0.27	0.27	0.31	0.27	0.30	0.25
w_j	0.07	0.10	0.09	0.09	0.07	0.08	0.08	0.08	0.09	0.08	0.09	0.08

SDV_j is the calculated standard deviation for each criterion.
W_j is the weight for each criterion

It is observed from the criteria weights in Table 5 that the most important criteria determining the country's performances are Total Deaths (C2), Current Health Expenditures (C9), and Cardiovascular Death Rate (C4). The least important criteria are, however, Diabetes Prevalence (C5), Total Cases (C1), and Total Tests (C12).

Table 6. Criteria Weights Comparison Matrix

	w_j	Total Cases (C1) 7.40%	Total Deaths (C2) 9.78%	Extreme Poverty (C3) 8.80%	Cardiovascular Death Rate (C4) 9.11%	Diabetes Prevalence (C5) 7.23%	Female Smokers (C6) 7.97%	Aged 65 + (C7) 8.06%	Male Smokers (C8) 8.10%	Current Health Expenditures (C9) 9.28%	Total Recovered (C10) 7.91%	Hospital Beds Per 1000 (C11) 8.84%	Total Tests (C12) 7.54%
Total Cases (C1)	7.40%		0.76	0.84	0.81	1.02	0.93	0.92	0.91	0.80	0.93	0.83	0.98
Total Deaths (C2)	9.78%	1.32		1.11	1.07	1.35	1.23	1.21	1.21	1.05	1.24	1.11	1.30
Extreme Poverty (C3)	8.80%	1.19	0.90		0.97	1.22	1.10	1.09	1.09	0.95	1.11	1.00	1.17
Cardio. Death Rate (C4)	9.11%	1.23	0.93	1.04		1.26	1.14	1.13	1.13	0.98	1.15	1.03	1.21
Diabetes Prevalence (C5)	7.23%	0.98	0.74	0.82	0.79		0.91	0.90	0.89	0.78	0.91	0.82	0.96
Female Smokers (C6)	7.97%	1.08	0.81	0.91	0.87	1.10		0.99	0.98	0.86	1.01	0.90	1.06
Aged 65 + (C7)	8.06%	1.09	0.82	0.92	0.88	1.11	1.01		1.00	0.87	1.02	0.91	1.07
Male Smokers (C8)	8.10%	1.09	0.83	0.92	0.89	1.12	1.02	1.00		0.87	1.02	0.92	1.07
Current Health Exp. (C9)	9.28%	1.25	0.95	1.05	1.02	1.28	1.16	1.15	1.15		1.17	1.05	1.23
Total Recovered (C10)	7.91%	1.07	0.81	0.90	0.87	1.09	0.99	0.98	0.98	0.85		0.89	1.05
Hospital Beds Per 1000 (C11)	8.84%	1.20	0.90	1.00	0.97	1.22	1.11	1.10	1.09	0.95	1.12		1.17
Total Tests (C12)	7.54%	1.02	0.77	0.86	0.83	1.04	0.95	0.94	0.93	0.81	0.95	0.85	

W_j is the weight for each criterion

As noted before, the standard deviation method determines the criteria weights based on the contrasting attributes. In other words, this method puts less importance if the attribute distributes more evenly among the alternatives, but places more emphasis if it differs significantly. From Table 5, it is seen that the number of cases and number of tests per one hundred thousand people are similar for the countries in the sample. However, the differences in the number of deaths per one hundred thousand and current health expenditures become prominent across countries.

Based on the weights in Table 5, we also construct the matrix in Table 6 to show the relative importance for any pair of criteria following De Nardo et al. (2020). This matrix is interpreted from left to right and it is not symmetric. For example, Table 6 indicates that the number of COVID-19 deaths is slightly more important than the deaths due to cardiovascular diseases (1.07) and the current health expenditures (1.05), but 1.32 times more important than the number of confirmed cases. The extreme poverty level is as important as the number of hospital beds. In fact, current health expenditures and the extreme poverty level are two of the criteria that show the biggest discrepancies among the sample countries. The diabetes level in a population, however, is the least important criterion in this analysis.

Table 7. The Results of the ROV Method

Countries	Results			
	u_i^-	u_i^+	u_i	Rankings
Thailand	0.59	0.03	0.60	1
Iran	0.52	0.11	0.58	2
Paraguay	0.54	0.08	0.58	3
Ecuador	0.52	0.09	0.57	4
Costa Rica	0.52	0.10	0.57	5
Dominican Republic	0.53	0.07	0.56	6
Mainland China	0.52	0.08	0.56	7
Argentina	0.46	0.19	0.55	8
Kazakhstan	0.49	0.12	0.55	9
Turkey	0.49	0.10	0.54	10
Malaysia	0.51	0.04	0.53	11
Colombia	0.45	0.13	0.52	12
Brazil	0.43	0.15	0.51	13
Russia	0.38	0.22	0.49	14
Armenia	0.37	0.21	0.48	15
Mexico	0.45	0.05	0.47	16
Albania	0.42	0.08	0.46	17
Indonesia	0.42	0.00	0.42	18
Georgia	0.28	0.20	0.38	19
Bosnia and Herzegovina	0.30	0.16	0.37	20
Bulgaria	0.28	0.18	0.37	21
Montenegro	0.22	0.22	0.33	22
Average			0.50	

After obtaining the criterion weights, we find the rankings of country performances in the struggle against COVID-19 by employing the ROV approach. Since the first three steps in the ROV approach are the same as the weighting procedure of the standard deviation model, the normalized decision matrix shown in Table 4 is used for the ROV method as well. The best and worst utility values are computed according to Eq. (7)

and Eq. (8). Next, for each alternative, the mid values (u_i) are calculated by using Eq. (9). According to these values, countries, which constitute the alternatives, are ranked. The overall results of the ROV method are given in Table 7.

The results in Table 7 demonstrate that Thailand, Iran, and Paraguay perform the best in the fight against the COVID-19 pandemic, while Bosnia and Herzegovina, Bulgaria, and Montenegro are the worst-performing countries. The average performance score is 0.4984. The starting point of the pandemic, mainland China has the 7th ranking.

From Table 7, it is seen that the high-performing countries have lower COVID-19 deaths, higher healthcare expenditures, lower poverty rates, and much lower rates of cardiovascular diseases. Bosnia and Herzegovina and Bulgaria, the countries with the lowest performance, have higher COVID-19 deaths and the highest elderly population in the sample. Montenegro is one of the countries with the lowest COVID-19 deaths. Since the beginning of the pandemic, Montenegro has applied strict physical distancing rules. However, when the population characteristics are closely observed, it is seen that smoking and diabetes are very common. The cardiovascular death rates are elevated. Together with the large elderly population, the struggle against the current pandemic becomes tougher.

Interestingly, the countries with the lowest performance have relatively high levels of current health expenditures and hospital bed capacity. In the case of Bulgaria, the lack of the medical workforce, especially in terms of nursing staff created difficulties for the treatment of COVID-19 disease. Particularly during the wave of October 2020, the number of infected medical professionals increased heavily and generated a shortage in workforce capacity[3]. The Bulgarian government was also criticized for not putting into force necessary non-healthcare precautions timely. The physical distancing rules were started to be applied late. Bosnia and Herzegovina, on the other hand, caught relatively short of the COVID-19 pandemic. There was no initial emergency action plan in the country for such a disaster. Although the healthcare resources are higher than the sample average in terms of expenditures and hospital beds, the resources seem to be inefficiently managed during the pandemic[4].

These findings indicate that each country struggles with this global health crisis with its own resources. Healthcare capacity and the amount of healthcare expenditure matter, albeit, are not enough. The efficient management of available resources and the existence of an emergency action plan are also necessary. In addition, these three countries have the highest elderly percentage in the sample. An older population increases the demand for long term healthcare attention (Yiğit, 2020). This situation raises the burden on the overall system particularly in times of crisis and limits the success of the "flattening the curve" efforts.

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[3]COVID-19 Health System Response Monitor (HSRM) https://www.covid19healthsystem.org/countries/bulgaria/livinghit.aspx?Section=2.2%20Workforce&Type=Chapter#7Physicalinfrastructure Access Date: 09.07.2021

[4] COVID-19 Health System Response Monitor (HSRM) https://www.covid19healthsystem.org/countries/bosniaandherzegovina/livinghit.aspx?Section=2.1%20Physical%20infrastructure&Type=Section Access Date: 09.07.2021

When we turn our attention to the Asian countries, we observe that Thailand, Malaysia, and mainland China are among the least affected countries by the COVID-19 pandemic in the world (Olivia et al., 2020). Thailand has a very low rate of COVID-19 deaths which brings the country to the first ranking. In fact, it is the only middle-high income country that has a position in the top ten health systems in the Global Health Security index ratings[5]. Together with mainland China, Thailand is among the countries that apply very strict measures since the beginning of the pandemic. The country had an influenza pandemic plan and people have been used to wear face masks because of previous epidemics and air pollution (Issac et al., 2021). Issac et al. (2021) indicate that the success behind Thailand's COVID-19 management is due to the primary healthcare workers that also surveil individual mobility and high usage of technological tools.

Mainland China has the 7th ranking in this comparison. China is known for its very restrictive measures since the beginning of the pandemic. On the global level, it has a low amount of total deaths due to effective coordination between its local and central administrations and the applied social control levels (Jiang, 2020). Comparing to the country figures in our sample, mainland China has COVID-19 deaths less than the sample average as well. It is position is mostly due to its averaged current healthcare expenditure levels and relatively higher cardiovascular death rates in society.

Malaysia has the average performance ranking according to our analysis (11th place). The country has lower COVID-19 deaths. Its population is relatively young and the cardiovascular deaths rates are close to the sample average. Hamzah et al. (2021) investigate the performance of Malaysia against COVID-19 very thoroughly with a network DEA approach. They examine the performance into three sub-areas, namely community surveillance, non-critical and critical medical care needs. They show that the highest inefficiency is originated from the medical care that must be applied to patients with critical conditions. The country demonstrates efficient contact tracking and surveillance, on the other hand. Hamzah et al. (2021) point out that this is mostly because of the existing emergency plans and the country's elevated preparedness levels. The inference of Hamzah et al. (2021) is also confirmed by our analysis. We observe that Malaysia has much lower current health expenditures than the sample average which lowers the position of the country and causes a middle ranking despite its high preparedness level.

In contrast to most Asian countries, Indonesia produces a much lower performance in the struggle against the pandemic. De Nardo et al. (2020) indicate that in low and middle-income countries, the poverty rates are higher, so implementing the social distancing rules is much difficult as well as accessing clean water. This is the case with Indonesia. It is mostly due to very high rates of extreme poverty, cardiovascular disease prevalence, low amount of hospital beds per capita (Olivia et al., 2020). Setiati and Azwar, (2020) point out that the number of beds in intensive care units per capita is among the lowest in Asian countries. They are mostly located in specific areas, so

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[5] This global index compares 195 countries according to 6 categories, including disease prevention, detection and reporting, and health system capabilities. According to this index, Thailand has an 73.2 index score and had 6th place out of 195 countries in 2019. https://www.ghsindex.org/about/ and GHS Homepage https://www.ghsindex.org/ Access Date: 06.08.2021

not evenly distributed. Healthcare workers cannot reach enough protective suits while dealing with COVID-19 patients. The country has also been criticized for reacting late to the initial cases while its neighbors, Malaysia and Singapore, had already started mass testing (Olivia et al., 2020).

Turkey has 10th place in the performance ranking. The country has lower health expenditures and hospital bed capacity than the sample average. It owes its relatively high position to the low number of COVID-19 deaths, much lower cardiovascular disease rates, and younger population. It had an influenza pandemic plan before the current pandemic which facilitated being prepared for the spread of this disease.

As noted by Jamison et al. (2020), the efforts of "flattening the curve" play a significant role in those rankings. The delay in the implementation of such measures can also be a determinant. Brazil, for instance, does not have a high rate of chronic diseases or deaths, has a relatively younger population and expenditures for the healthcare system as a percentage of GDP are relatively higher. However, the Brazilian government has minimized the necessary precautions. The social distancing implementations are very weak and the extreme poverty in the country is high. This explains the very high rates of deaths related to COVID-19.

In contrast to Brazil, the countries located in central and south America mostly demonstrated good performance against COVID-19. Paraguay, Ecuador, Costa Rica, and the Dominican Republic have positions from 3rd to 6th in the sample. Among these countries, Ecuador and Costa Rica have advanced Global Health Index rankings[6]. The population percentage of 65 years and over is relatively small in Paraguay. The country also experiences a small number of COVID-19 deaths. UNDP Paraguay report (2020) reveals that the country was fighting the Dengue epidemic when the COVID-19 pandemic started. Because of the previous experience from the Dengue outbreak, the Paraguay government responded quickly to this new disease and applied physical distance measures and movement restrictions early.

We observe that a bigger healthcare capacity and lower poverty levels maintain a strong stance against health system crises even with higher levels of disease spread. As the healthcare system becomes larger and more evenly distributed, this battle gets easier. However, as we see from the Bosna and Herzegovina example, the efficient usage of the existing capacity is crucial to be successful. The initial preparedness of the countries and their willingness to apply social distancing measures are also important to limit the number of deaths. Brazil, for example, has a relatively greater overall score in the rankings of the Global Health Security Index. However, the government's reluctance to put in force necessary measures caused a significant number of deaths.

Poverty levels, on the other hand, determine the applicability of non-healthcare precautions. In the countries where most of the population lives below the poverty line, it is almost impossible to achieve physical distancing and personal hygiene. This environment accelerates the new numbers of COVID-19 cases. Taken together with the limited healthcare facilities, it is natural to observe a higher number of deaths.

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[6] https://www.ghsindex.org/country/ecuador/ and https://www.ghsindex.org/country/costarica/ Access Date: 06.08.2021.

5. Sensitivity Analysis

To show that our findings from the SDV based ROV approach are robust, we also conduct TOPSIS and EDAS analyses and compare the results. As discussed before, the ROV method depends on the comparison of best and worst utility functions for each alternative. Based on these utility functions, we obtain the rankings of alternatives in an easy manner. TOPSIS method, which is widely used in different areas (for example, Mimović et al. 2021), computes distances from positive ideal and negative ideal solutions. The alternative is ranked based on its proximity to the positive ideal and its remoteness from the negative ideal. The EDAS method, however, calculates the distances from average solutions. The positive and negative ideals are not required to be estimated (Ghorabaee et al., 2015).

We apply both TOPSIS and EDAS methods by employing the criteria weights obtained from SDV analysis. The comparisons of the rankings from these three methods are demonstrated in Figure 2.

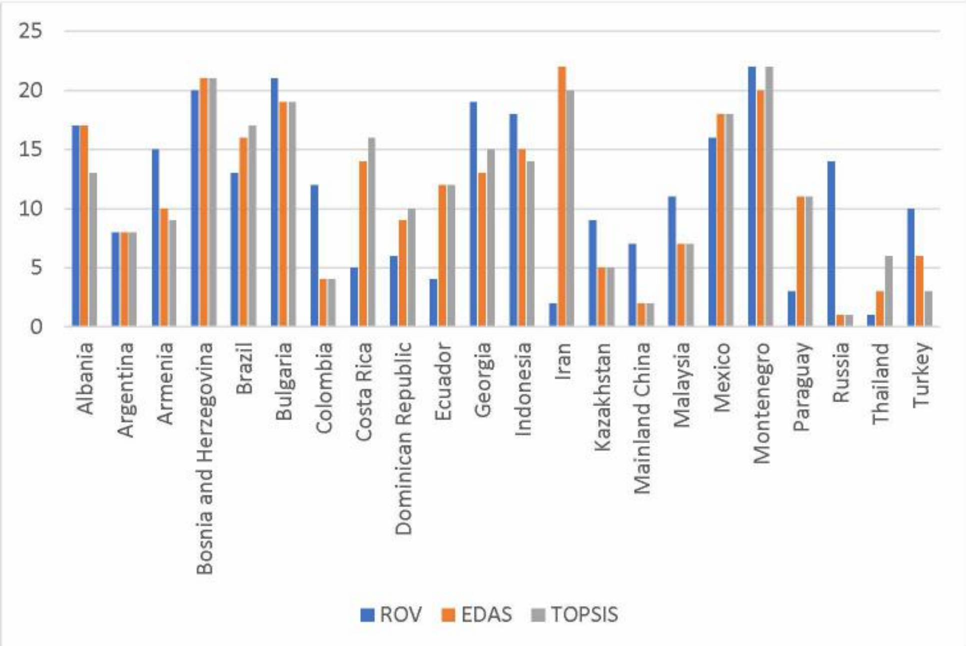

Figure 2: The rankings from ROV, EDAS, and TOPSIS methods respectively

The comparisons show that the rankings from these three methods are quite parallel to each other. Particularly, the rankings of the low-performing countries stay very similar. In addition to the visual analysis, we also look at the Spearman rank correlations and Wilcoxon rank tests. The former one is applied to observe the direction and strength of the relation between the ranks obtained from these three methods. The latter test shows whether the mean ranks are statistically different. Both are non-parametric tests since MCDM analysis provides results that are not normally distributed. The findings are presented in Table 8.

Table 8. The Results for Spearman Rank Correlations and Wilcoxon Rank Tests

Spearman Rank Correlations			
	ROV	EDAS	TOPSIS
ROV	1		
EDAS	0.69	1	
TOPSIS	0.61	0.97	1
Wilcoxon Rank Tests			
H_0	ROV=EDAS	ROV=TOPSIS	
Z	0.488	0.261	
p-value	0.626	0.806	

The findings from Spearman rank correlations indicate that the ROV method produces positive and fairly high association with EDAS and TOPSIS methods (0.69 and 0.61 respectively). In the second part of Table 8, the mean ranking of ROV is tested against EDAS and TOPSIS. The null hypotheses here are the mean ranking of ROV is not different than the mean ranking of EDAS and TOPSIS respectively (first and second columns). The p-values for both tests are much higher than any acceptable significance levels, so the null hypotheses cannot be rejected.

The overall results suggest that the ROV method has a computational advantage over more popular methods such as TOPSIS and EDAS and offers similar rankings.

6. Conclusion

This study aims to shed light on the black-box nature of the COVID-19 pandemic by comparing the country's performances in this global struggle. To do so, the performance of 22 countries, which all belong to high–middle income group according to the World Bank classifications, are assessed. Since several and conflicting criteria are used, the performance ranking against managing the current pandemic is considered a multicriteria decision-making problem. The benchmarking is made with the standard deviation-based ROV approach. To the extent of our knowledge, this is the first study that combines these two methods and applies them to the COVID-19 pandemic.

In the struggle against COVID-19, there are some important parameters such as the properties of the healthcare system, application of physical distancing rules and mobility restrictions, and the population characteristics. Among them, particularly the healthcare capacity, proxied by the number of hospital beds and the current healthcare expenditures, becomes prominent. Our analysis confirms this expectation and demonstrates that Thailand has the highest ranking in our sample. The country's very high position in the Global Health Security Index and the very low number of COVID-19 deaths are no surprise, in this sense. However, the findings from the lowest ranking countries reveal that the efficient usage of healthcare resources matters as much as its amount. These countries have a relatively high amount of healthcare resources, but they have still experienced elevated numbers of COVID-19 deaths. As seen from the Bosnia and Herzegovina case, the lack of an emergency healthcare plan makes much more difficult to obtain efficiency in the usage of resources.

We also observe that the high-ranked countries are mostly praised for their quick response to take necessary non-healthcare restrictive precautions and the low-ranked ones are highly criticized for the same reason. It is seen that many Asian countries, for instance, Thailand, mainland China, and Malaysia, applied strict social distancing rules, whereas Brazil, Bulgaria, and Indonesia are the ones where these rules are weak or sometimes non-existent.

Our analysis also confirms that population characteristics are other determinants of country performances against COVID-19. The low-ranking countries mostly have an elder population. Age brings co-morbidities with itself which increases the likelihood of COVID-19 deaths. It also boosts the requirement of long-term healthcare attention, which creates another burden on the already overwhelmed healthcare system. Another population characteristic that affects country rankings is the level of poverty. In countries, where the poverty level is higher, implementing the social distancing rules and distant working becomes almost impossible. In fact, we show that extreme poverty is as crucial as the number of hospital beds in this battle. Combining the fact that these areas have diminished access to clean water, the spread of the disease is inevitable. This is one of the social consequences of COVID-19: It contributes to the gap between rich and poor. Policymakers should consider policies that decrease the level of poverty to control future pandemics as well. The vaccination policies against COVID-19 will also have importance. Since the delivery of vaccines requires more time in the middle-high income countries in comparison to their developed counterparts, the public must comply with the social distancing rules to avoid future deaths.

For future pandemics, countries that manage their healthcare resources more efficiently and that are quick to apply social distancing rules will be more successful to eliminate the negative impacts. However, policymakers must also focus on elderly care and poverty levels in their countries.

There are some limitations of this study that must be mentioned: First, the very quick changes in the pandemic landscape restrict the generalizability of the findings to some extent. This is why the COVID-19 studies that compare the beginning of the pandemic to the ongoing situation are valuable. Second, we have only used quantitative data in this analysis. Further researches may consider qualitative data and appropriate techniques such as fuzzy MDCM to compare the performance of countries. Last, at the beginning of the pandemic, the definitions of COVID-19 deaths and patients were not clear for all countries[7]. In time, there has been a convergence in these definitions. However, this situation may create a limitation for this study in terms of comparability.

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[7]Some countries have made a distinction between "deaths *from* COVID-19" and "deaths *with* COVID-19". The same difference was valid at the beginning of the pandemic for the positive cases. Some counted a person as COVID-19 patient depending on the clinical diagnosis, others required a positive test result.
Source:https://eurohealthobservatory.who.int/monitors/hsrm/analyses/hsrm/how-comparable-is-covid-19-mortality-across-countries Access Date: 05.08.2021

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REGIONAL DEVELOPMENT THROUGH ENERGY INFRASTRUCTURE: A COMPARISON AND OPTIMIZATION OF IRAN-PAKISTAN-INDIA (IPI) & TURKMENISTAN-AFGHANISTAN-PAKISTAN-INDIA (TAPI) GAS PIPELINES

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Abstract: *Pakistan is working on two pipeline projects, namely, Iran-Pakistan-India (IPI) and Turkmenistan-Afghanistan-Pakistan-India (TAPI) gas pipelines, to meet its energy supply-demand gap. This study's aims to compare these two projects and identify the most suitable option for Pakistan. Furthermore, as the TAPI project is progressing faster than the IPI project, this study also aims to identify the critical activities associated with TAPI projects. Finally, a model is proposed to optimize the material and transportation costs related to the TAPI project. The study's contribution by using fuzzy set theory-based multi-criteria decision-making (Fuzzy MCDM) to compare two projects along with usage of the Fuzzy Critical Path Method (FCPM) for the identification of critical activities associated with the TAPI project. Finally, the Genetic Algorithm is applied to optimize the material and transportation costs of the TAPI project. The results show that IPI has advantages over TAPI in terms of power generation, transportation cost, transits fee, and gas prices. The critical path analysis of the TAPI gas pipeline shows that it will take approximately 75 to 330.5 weeks to complete. The study is useful for the managers who have to work in these projects, the policymakers considering these projects at various levels, and the researcher having an interest in applying Fuzzy set theory with MCDM, CPM, and in the context of the energy infrastructure.*

Key words*: Optimization models, Fuzzy TOPSIS, Fuzzy CPM, Genetic Algorithm, MCDM, TAPI, IPI*

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1. Introduction

Pakistan is confronted with increasing energy demand and the energy demand-supply gap (Ali, et al., 2020a). Pakistan's energy mix is dominated by thermal sources, mainly imported from Middle East countries (MoF, 2020). Although Pakistan has been producing oil and gas locally, it is insufficient to meet its energy demand (MoF, 2020). Pakistan's geographic closer locations to oil-rich middle-eastern countries and its land connection with Iran and natural gas-rich Central Asian States (via Afghanistan) give it a geographic advantage. Historically, Pakistan has heavily relied on oil imports from the Kingdom of Saudi Arabia (KSA) and the United Arab Emirates while ignoring the neighbour Iran mainly due to economic sanctions on Iran.

To meet its growing energy demand, Pakistan has been exploring multiple options. These options include an increase in local exploration of energy sources and identifying and connecting to importing energy resources from other countries. In this regard, there has been a discussion on projects like the Iran-Pakistan-India (IPI) pipeline that was planned to connect these three countries for gas supply from Iran. However, the IPI project could not be implemented according to the expectations and plans due to international sanctions on Iran and pressure from the United States and KSA. The alternative to the IPI pipeline project that is proposed, debated, and supported by the stakeholders is Turkmenistan-Afghanistan-Pakistan-India (TAPI) gas pipeline. TAPI has support from both the USA and the KSA. However, there are concerns over the safety and security of the TAPI pipeline, especially across Afghanistan. Also, there are issues with funding for the project. However, currently, the IPI pipeline project is not progressing significantly compared to the TAPI pipeline project.

This study has two main objectives. First, the study does a feasibility comparison of IPI and TAPI gas pipeline projects for Pakistan. We consider several factors such as capacity, length, costs and other associated benefits and costs of these two projects to undertake its feasibility. Secondly, given the fast progress on the TAPI project, the study also identifies the critical activities being involved in the TAPI pipeline project and suggests cost optimization that may help implement the TAPI pipeline project. Finally, the study also proposes a model to optimize the material and transportation costs related to the TAPI project. To the best of our knowledge, no such analysis is undertaken for these two projects. The major contribution of this study is the first of its type comparison of the IPI and TAPI pipelines project and the application of fuzzy set theory based multi-criteria decision method (MCDM) TOPSIS (Technique for Order Preference Similarity to Ideal Solution) and Critical Path method (FCPM) along with the application of a genetic algorithm for the optimization of TAPI project. These techniques are not employed in such a context in earlier literature. Thus, the study contributes also in terms of the application of advanced decision-making techniques in feasibility studies.

The rest of the study is organized as follows: Section 2 is a Literature review. Section 3 consists of an overview of the IPI and TAPI pipeline projects and their comparison. Furthermore, Section 4 presents the fuzzy TOPSIS, Fuzzy CPM, and Genetic Algorithm and the various steps associated with each method. This section also describes the data and the sources used in this study. Section 5 presents the results of the study. Finally, section 6 concludes the study.

2 Literature Review

The literature review section is divided into subsections. The first subsection discusses studies associated with IPI and TAPI projects. The second subsection discusses the studies on the methodological aspects of these studies

2.1 The literature on IPI and TAPI projects

There are various aspects of scholarly studies focusing on IPI and TAPI projects. For instance, several studies discuss feasibility aspects (economic or political) of TAPI or IPI projects. Some researchers discuss both projects together while considering a single-country perspective. The feasibility studies covering either TAPI and IPI or even both are undertaken from different project partner countries. For instance, Pandian (2015) studied the Indian perspective for the IPI project. Similarly, Hudaa & Ali (2017) covers the TAPI project from Pakistan's perspective. Below we discussed scholarly studies that are explored these two projects from different member countries' perspectives.

The study of Pandian (2005) does discuss the IPI project from the Indian perspective. The research performed a qualitative cost-benefit analysis and argued that the IPI project could work as a confidence-building between India and Pakistan to create an energy partnership between the two countries and open up more possibilities for commercial businesses. Sahir & Qureshi (2007) examined the Pakistani perspective on the region's energy security and its role as an energy corridor. The study also briefly describes Pakistan's importance for pipeline projects (such as IPI and TAPI) that could meet India and China's energy needs along with benefits to Pakistan. Similarly, Abbas (2015) describes a brief history of IPI and TAPI projects in Pakistan's energy needs. Also, Pradhan (2020) described in detail the TAPI project and its importance for India. The study also detailed the reasons for delays in the project and the lack of interest of international firms to finance the TAPI project.

The IPI project is vital for India because it will provide a four-time cheaper gas than other sources, even after paying the transit fee to Pakistan (Pradhan, 2020). Furthermore, the project will bring earnings for Pakistan and improve energy security in both India and Pakistan. The project could ensure a path for energy and trade connectivity across the South-Asia. However, as per Pradhan (2020), Pakistan and India disagree on the transits fee. Furthermore, India has concerns over the continuation of supply in case of a rise in political conflict. KSA is not in favour of this project. But, China has shown interest in participating in the IPI project. In this situation, Pakistan can still enjoy transits country status (Pradhan, 2020).

Mahmood et al. (2014) studied to make assessments for Pakistan's energy needs. So the study assesses the energy that Pakistan can obtain from various energy sources and do discuss the energy import options from IPI and TAPI gas pipelines. The study describes these projects' potential to meet Pakistan's future energy needs and consider energy from other possible sources. However, Mahmood et al. (2014) do not undertake direct feasibility studies of these projects or make any comparison. Similarly, Munir et al. (2013) is also not a full feasibility study. However, Munir et al. (2013) referred to the IPI project as viable for Pakistan with a net reduction of import bill by US$2.3 billion annually with generating 4000 MW of electricity. However, the international geopolitical conditions and the Iran economic sanctions were considered a point of concern for this project's success for Pakistan.

It is essential to highlight the geopolitical conditions that strongly influence both these projects in South and Central Asia. There are various aspects of international politics and countries like the USA, China, Russia, Saudi Arabia, and the member countries of the project. There are abundant studies that discuss various aspects of international relations and geopolitics and their impacts on these projects. For instance, Hudaa & Ali (2017) emphasized increasing the number of stakeholders in mega projects (like TAPI) beyond the member countries. They argue that such an approach may bring a better political consensus and earn more significant support and the shifting focus from the projects' security to inclusiveness and cooperation.

Lee (2014) explored the opportunities for diversification of Turkmenistan gas export routes and related risks. The study also highlights the TAPI project from Turkmenistan's perspective, discusses the various international events and China's role, and argues that these events are causing delays in implementing the TAPI project. Anceschi (2017) interestingly called TAPI a virtual pipeline, given its delays and misinformation around the project while no work was started on its implementation. Furthermore, Anceschi (2017) referred to some studies and raised concerns about the overall viability and security concerns particularly that of the 750 lengths planned to be in the Afghanistan region. Similarly, Khan (2012) focused on the IPI pipeline project, the USA sanctions, and its resultant situation and its implementation for Pakistan and other countries involved.

The other aspect of the project is its safety and security. In particular, for the TAPI project as passes through Afghanistan. India has concerns over the project's safety and security, especially if it has not a good relationship with Pakistan. For instance, Pradhan (2020) highlights concerns over the pipeline's protection in Afghanistan and the Pakistan-Afghanistan border region. The study also insisted that the gas supply should be ensured, and a proper mechanism should be placed that must be independent of the Pakistan-India political relations. The study refers to the project as a win-win for all the participating member countries.

The recent delays in these project implementations are also of concern for the partner countries. Sadat (2015) describes five phases for the implementation of TAPI phases. Accordingly, the first few phrases that required signing the framework and agreements, sales, and purchases of gas agreements are already completed. However, other aspects, in particular, the implementation of the project itself is not completed. Sadat (2015) referred to security, scarcity of the required funds, diplomatic relationships of the member countries, and alternative energy sources' availability as significant delays on further progress on the TAPI project. Joshi (2011) studied the economics and politics associated with the TAPI pipeline and refer it to a plan that does not proceed beyond discussion due to Afghanistan and Pakistan's conditions, thus suggesting that India explore alternative options and courses of action for its energy needs.

More recently, Rajpoot & Naeem (2020) did the feasibility of the TAPI project. They emphasise the TAPI project as being more valuable for meeting the energy crisis of Pakistan and India. However, the study has not employed any decision making or advanced techniques instead is based on published literature and media reports. According to, Khetran (2020), for successful implementation of TAPI the bilateral relationship between India, Pakistan, and Afghanistan is important. Rajmil, et al.

(2021) debated the nature of the relationship between China, Iran and Pakistan in form of their common economic corridor. Accordingly, they argue that despite their partnership being built through Belt and Road Initiative investments, but future of such relations mainly depends on the mutual relationship between Pakistan and India. All these developments have implications for the implementations of TAPI and IPI projects.

2.2 Research methods used for studying IPI and TAPI projects

The studies discussed above are mainly based on qualitative techniques. For instance, Khetran (2020) (based on published media reports and scholarly articles), Hudaa & Ali (2017) (interview of policymakers), Pandian (2005) (qualitative cost-benefit analysis), Sahir & Qureshi (2007) (regional geopolitical and energy concerns), Abbas (2015) (energy needs), and Anceschi (2017) (qualitative analysis). Furthermore, these studies are mostly focused on a single project (TAPI or IPI) from a unique country perspective and with a lack of applying formal economic viability or feasibility techniques. Even if some studies discussed both projects, it does not go beyond the deceptive analysis.

The scholarly literature on infrastructure projects does employ several methods for analyzing the economic viability of infrastructure projects. The most popular among these techniques are traditional cost-benefit analysis (e.g., Ali et al., 2020b). Some other popular techniques are Net Present Value (Ali et al, 2021) and Internal Rate of Return (Ali et al 2021). Another interesting application is that of MCDM based cost-benefit analysis (e.g., Bilal, et al. 2021). Since TAPI and IPI are mega projects, going through multiple countries and have a lot of technical complications, therefore using the traditional method of feasibility (such as cost-benefit analysis) may not be useful due to the absences of the finest data details. Therefore, in the absence of such information, multi-criteria-based decision-making (MCDM) techniques become more relevant for analysis.

This study, therefore, has two major objectives. The study aims to compare IPI and TAPI projects based on several factors (capacity, pipeline lengths, project costs, associated benefits and costs). Due to the unavailability of detailed project data, the study uses MCDM based methodology namely, fuzzy TOPSIS (Technique for Order Preference Similarity to Ideal Solution) (Gopal and Panchal, 2021). Furthermore, the study aims to identify the critical activities in the implementation of the TAPI project, as Pakistan is currently implementing this project. For this purpose, the study uses the fuzzy Critical Path method (FCPM). Finally, the study also aimed to optimize the resource usage in the TAPI project, for which the study employed a genetic algorithm. Thus, the study not only does employ advanced decision-making techniques (i.e., fuzzy MCDM) but also apply them in combination with Fuzzy CPM and genetic algorithm. No previous studies (to the best of our knowledge) on the subject projects or in such context has applied such methodology earlier. Thus, the study contributes to the literature not only by providing a new approach to undertake the feasibility studies of similar projects, but also providing a useful policy direction for the decision-makers associated with TAPI and IPI projects.

3 TAPI and IPI: background

The Turkmenistan-Afghanistan-Pakistan-India (TAPI) and Iran-Pakistan-India (IPI) pipelines are important infrastructure projects for Pakistan's future energy needs. These two international energy supply pipeline projects will be the first of their kind in this region. Below we briefly describe these two projects and presents some relevant details about each of them.

3.1 Turkmenistan-Afghanistan-Pakistan- India (TAPI) gas pipeline project

TAPI project will start from gas fields in South Yolotan Turkmenistan (Galkynysh and adjacent gas fields) and link to Quetta (Pakistan) through the Afghanistan areas of Herat, Nimruz, and Kandahar. In Pakistan, it goes through the Dera Ghazi Khan, Multan, and then onward to Fazilka (India) (Hudaa & Ali, 2017). Figure 1 presents the approximate route of the TAPI gas pipeline project. This pipeline is approximately 1680 km long, with 56-inch pipe diameter, and has a capacity to supply about 3.2 (bcfd) per day gas supply that will be shared between Afghanistan (500 mcfd), Pakistan (1325 mcfd), and India (1325 mcfd) (ISGS, 2020). The cost of the project is estimated to be about US$ 7.74 billion (ADB, 2020).

Figure 1. TAPI and IPI project locations (source: Google maps)

TAPI project is essential for Pakistan for several reasons. The gas supply from the project can be used in power generation in Pakistan (Gas through the TAPI pipeline can generate 6,000 megawatts cheaper electricity (Naseem, 2015). This electricity is more than the current electricity generation of the largest Pakistan Tarbela Dam). Although, Pakistan recently ensured LNG from the Central Asian states, however, it will still face the shortages for its need that has been tried to manage with its domestic production (ADB, 2020). Furthermore, the project can ensure a consistent supply of foreign exchange for project life duration in royalty payments from India. Additionally, project construction and operations can lead to further public and private investments and job creations, leading to more economic activities. The intangible benefits could be the improvement in India and Pakistan's relationship, resulting in a peace process in this entire region.

TAPI project would be of equal benefits to India, Afghanistan, and Turkmenistan. Indian economy energy demand is on the rise, and they would be able to get cheaper gas supplies at their doorstep. Afghanistan will earn in royalty from both India and Pakistan, along with creating jobs and employment opportunities that are almost non-existent in their country at the moment. It will be an opportunity for Turkmenistan to expand its energy market and build a more strategic relationship with its customers in the region. According to D'Souza (2017), the TAPI gas pipeline is a game-changer for the countries that are part of it. It will improve their economy and fulfil their energy requirements and eventually become the primary source of enhancing the people's lifestyle in South and Central Asia.

3.2 Iran-Pakistan-India (IPI) gas pipeline project

The Iran-Pakistan-India (IPI) pipeline as a project idea can be traced back to the 1950s. However, the main proposal was placed during 1989, and the three governments agreed upon it during 1999 (Baluch, 2012). The Indian government has withdrawn from the project during 2009. However, the Indian government can still reconsider their decision and later join the project (Haq, 2010). Therefore, we will be considering India as a part of this project while comparing IPI and TAPI in this study.

The IPI project cost is US$ 7.6 billion, with a total capacity of 5.3 billion cubic feet of gas per day, with Pakistan and India share as 2.1 and 3.2 BCFD, respectively. The project was expected to provide about US$ 700 million in transit revenue to Pakistan (MoF, 2007). Pakistan is responsible for constructing a pipeline network on its side, whereas Iran has to build its part. However, currently, due to sanctions on Iran, there is no major progress on the project.

This project is essential for Pakistan because it will provide Pakistan not only, supply of gas from Iran but also will provide much needed foreign exchange in the form of transit fees from India.

3.3 Comparison of TAPI and IPI projects

It is essential to highlight that Pakistan has considered both TAPI and IPI projects due to its energy increasing demand. Due to international geopolitical conditions and Iran's position, Pakistan has been under pressure to prefer the TAPI gas pipeline project over the IPI gas pipeline project. Some studies recommend that the TAPI gas pipeline project is not feasible because of the low gas quality and the unstable situation of Afghanistan (Mazhar & Goraya, 2013).

Furthermore, the TAPI project will be facing significant security challenges due to its passage from Afghanistan, where there are various militant and nationalist troubles, especially in the area of the project (Khetran, 2017). Although Afghanistan will provide full security for the project, India has preferences for it (Khetran, 2017). In the Pakistani region, the TAPI project has no significant threats as it may have in Afghanistan.

Contrary to Mazhar & Goraya (2013), the study from (Kulkarni 2016) refers to the TAPI project as feasible only if its geopolitical and commercial prospects are considered. Similarly, about 99 per cent of the respondents to a survey (in Afghanistan) during 2019 supported this project and viewed it as a role model project for the other national development projects (Saqib, 2019). Finally, the USA is also supporting the TAPI project compared to the IPI project (Hudaa & Ali, 2017) because of sanctions on Iran and its deteriorating relations since the Islamic revolution in Iran back in the 1970s.

The IPI project is facing many challenges. Perhaps the primary problem is that Iran is under United Nations economic sanctions that is a big hurdle for Pakistan and Iran to proceed on this project. Not much progress has been made in more recent years. There have been renegotiations on the same clauses of the project agreement, to make it more workable for the future. There is some comparison provided in Table 1 below for the two projects.

Table 1. Basic statistics of IPI and TAPI projects

Details	IPI	TAPI
Pipeline length (kilometers)	2,775	1,735
Pipeline diameter (inches)	56	56
Pipeline capacity (bcfd*)	5.3	3.2
Project Costs (US$ billions)	7.6	7.74
Global risk factors	Iran sanctions	Nil
Internal risk factor	Political conditions	Safety and Security

* Billion cubic feet per day

Sources: (ADB, 2012; Mahmood, et al., 2014; Hudaa & Ali, 2017; ADB, 2020 and Pradhan, 2020)

4. Research Methodology and Data

This study has multiple objectives. It aims to perform a feasibility comparison of IPI and TAPI projects. Secondly, it identifies the critical activities and optimizes the TAPI pipeline project's material and transportation costs. Therefore, the study uses *fuzzy TOPSIS*, *Fuzzy Critical Path Method (CPM)*, and *Genetic Algorithm*. We divided this section into several subsections and described the applications of each of these methodologies. The last sub-section describes the data used in this study.

4.1. Fuzzy Technique for Order Preference by Similarity to Ideal Solution

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is one of the well-known techniques that are used for Multiple-Criteria Decision Making (MCDM). TOPSIS was introduced by Ching & Kwangsun, (1981) and later modified by Tung, (2000). This technique has been extensively used in various fields, including operations (Ali, et al., 2019), supply chain (Ali, et al., 2020a), and economics (Ali, et al., 2019). The basic idea of TOPSIS is to help in selecting an alternative (among a set of available options) that is closest to the Ideal Positive Solution and farthest from the Ideal Negative Solution. TOPSIS uses linguistic scales for weights.[1] Tung (2000) modified linguistic scales for weight by using fuzzy triangular values, i.e., a fuzzy version of the TOPSIS environment. Fuzzy TOPSIS is also in use in scholarly literature in many applications, for instance, decision making (Khan, et al., 2020), economic development (Bin Hameed, et al., 2020), and supply chain (Ertuğrul & Karakaşoğlu, 2008). Figure 2 shows the typical steps involved for the TOPSIS approach (Minatour, et al., 2015) that are adopted in this study.

Figure 2. Illustrating typical steps in the TOPSIS approach (Minatour, et al., 2015)

The TOPSIS procedure can be described as follows.

Assume that there are N decision-makers with y alternatives among which they have to choose while using y criteria. The various steps for this decision making using Fuzzy TOPSIS will be as follows:

Step 1: In the first step of the Fuzzy TOPSIS procedure, N decision-makers compare all alternatives with a given criterion and then rate each alternative with respect to each criterion.

Step 2: The criteria receiving the most number of selections is taken for criteria weight and fuzzy numbers rating respectively as per set weight criteria. This study adopted the following (Table 2) Linguistic Variable weighting for each criterion.

Table 2. Linguistic variables use for weighting each criterion

Linguistic Variable	Triangular Number
Very High	(1.00,0.25,0.00)
High	(0.75,0.15,0.15)
Moderate	(0.50,0.25,0.25)
Low	(0.25,0.15,0.15)
Very Low	(0.00,0.00,0.25)

Source: (Izadi, et al., 2013)

Step 3: In this step, we will select the appropriate linguistic variable from Table 2 to find the importance weights of different criteria assigned by decision-makers. Weights are assigned to different responses obtained from decision-makers

$$\overline{W_j} = \frac{1}{K}\left[\breve{w}_j^{\,1} + \breve{w}_j^{\,2} + \ldots + \breve{w}_j^{\,k}\right] \quad (1)$$

Where $\overline{W_j}$ weight of different criteria assigned by decision-makers.

[1] A linguistic scales for weights extracted from Izadi, et al., (2013) is presented in Table A2 in Appendix.

Step 4: In this step, we will select appropriate linguistic variables from Table 1 to find the importance rating of different alternatives for criteria.

$$\breve{x}_{ij} = \frac{1}{K}\left[\breve{x}_{ij}{}^{1} + \breve{x}_{ij}{}^{2} + \ldots + \breve{x}_{ij}{}^{k}\right] \tag{2}$$

Where $\breve{x}_{ij}{}^{k}$ Is the rating of Kth decision-maker, against alternatives *i* and criteria *j*.

Step 5: Now in this step we will convert linguistic variables evaluation into fuzzy triangular numbers to construct a fuzzy decision matrix as well as determine the fuzzy weight of each criterion. i.e.

$$\begin{array}{ccc} & & \begin{array}{cccc} C_1 & C_2 & \ldots & C_n. \end{array} \\ \tilde{A} = & \begin{array}{c} A_1 \\ \vdots \\ A_m \end{array} & \begin{bmatrix} \breve{x}_{11} & \breve{x}_{12} & \ldots \breve{x}_{1n} \\ \breve{x}_{21} & \breve{x}_{22} & \ldots \breve{x}_{2n} \\ \breve{x}_{m1} & \breve{x}_{m2} & \ldots \breve{x}_{mn} \end{bmatrix} \end{array} \tag{3}$$

Similarly weight:

$$\overline{W_j} = [w_1 \quad w_2 \quad \ldots \quad w_n], \breve{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}) \tag{4}$$

Where $\breve{x}_{ij}$ represent a triangular fuzzy number. $A_1, A_2 \ldots \ldots A_n$ Are alternatives and $C_1, C_2, \ldots \ldots C_n$ are criteria.

Step 6: In this step, we will construct a normalized fuzzy decision matrix from above step 5. To avoid lengthy and complex formulation we use a Linear scale so $\bar{R}$ gives normalized values;

$$\bar{R} = [\tilde{r}_{ij}]_{m\times n} \tag{5}$$

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), C_j^* = \max c_{ij} \tag{6}$$

Step 7: In this step, we will construct a weighted normalized fuzzy decision matrix.

$$\dot{U} = [\tilde{u}_{ij}]_{m\times n} \quad \text{i = 1, 2, 3.....m} \quad \text{j=1, 2, 3....n} \tag{7}$$

$$\tilde{u}_{ij} = \tilde{r}_{ij} \times W_j \tag{7a}$$

Step 8: This step will determine the fuzzy positive ideal solution (FPIS) as (F^*) as well as fuzzy negative ideal solution (FNIS) as (F^-) mentioned in the below equations.

$$F^* = \tilde{u}_1^*, \tilde{u}_2^*, \ldots\ldots \tilde{u}_n^* \tag{8}$$

$$F^- = \tilde{u}_1^-, \tilde{u}_2^- \ldots\ldots \tilde{u}_n^- \text{ where } \tilde{u}_j^* = (1,1,1) \text{ and } \tilde{u}_j^- = (0, 0,0), \text{j= (1, 2 ... n)} \tag{8a}$$

Similarly, the distance between two fuzzy numbers can be calculated by vertex method i.e. if X and Y are two fuzzy numbers;

X= (a, b, c) Y= (x, y, z) then

$$D(X, Y) = \sqrt{\frac{1}{3}[(a-x)^2 + (b-y)^2 + (c-z)^2]} \tag{9}$$

Step 9: This step will determine the distance from a negative and positive ideal solution.

D steric = $\sum_{j=1}^{n} d(\tilde{u}_{ij}, \tilde{u}_j^*)$ (10)

D negative = $\sum_{j=1}^{n} d(\tilde{u}_{ij}, \tilde{u}_j^-)$ where d shows the distance between two fuzzy numbers

Step 10: This step will determine the closeness factor of each criterion.

$$CC = \frac{\text{D negative}}{\text{D steric} + \text{D negative}} \quad (11)$$

Step 10: Rank the given criteria on basis of the closeness factor. The criteria having more closeness factors will be chosen best in descending order.

4.2. Fuzzy Critical Path Method (FCPM)

The Fuzzy Critical Path Method (FCPM) is based on fuzzy set theory. Fuzzy set theory was introduced by Zadeh, (1996). The fuzzy approach is useful in a decision situation when the past data are not available or relevant (Liberatore & Matthew, 2002). The fuzzy Set theory approach is applied now in every field of technology (Aziz, 2013) and has many applications in various fields, including artificial intelligence, computational intelligence, and data analysis (Mares, 2006).

A project manager may use the Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) to manage, monitor, and control project activities. PERT is considered more realistic because it provides three-time durations (most likely, pessimistic and optimistic) of the activities (compared to only one in CPM). These time values are obtained from experts, and the beta distribution is also used (Ramo, 2014). On the other hand, Fuzzy CPM helps plan and control difficult projects like IPI or TAPI. The basic logic behind Fuzzy CPM is the same as simple CPM, but fuzzy triangular numbers or trapezoidal fuzzy numbers are used in Fuzzy CPM. It helps in the identification of critical activities in the Network critical path. Furthermore, it can be employed for gas pipeline construction projects to identify various related activities and critical paths to complete projects without delay. An arithmetic operation can be done on any generalized trapezoidal fuzzy numbers. For example, consider two trapezoidal fuzzy numbers $X = (U_1, U_2, U_3, U_4)$ and $Y = (V_1, V_2, V_3, V_4)$, then the summation and subtraction are (Vahidi & Rezvani, 2013):

$$X + Y = (U_1, U_2, U_3, U_4) + (V_1, V_2, V_3, V_4) = (U_1 + V_1, U_2 + V_2, U_3 + V_3, U_4 + V_4) \quad (12)$$

$$X - Y = (U_1, U_2, U_3, U_4) - (V_1, V_2, V_3, V_4) = (U_1 - V_4, U_2 + V_3, U_3 + V_2, U_4 + V_1) \quad (13)$$

Now, to describe the Fuzzy Critical Path Method (FCPM) technique following notations are used:

N_d:	Nodes in the project network diagram
Act_{ij}:	Activity between the nodes
AFT_{ij}:	Activity fuzzy time of Act_{ij}
FET:	Fuzzy earliest time
FLT:	Fuzzy latest time
FST_{ij}:	Total fuzzy slack time of Act_{ij}
$FCT(P_n)$:	Fuzzy completion time
Num:	Number of activities in our project network diagram

Fuzzy Critical Path Method (CPM) may be applied using the following steps:

Step 1: Consider the fuzzy earliest time (FET_1) value (0, 0, 0, 0).

Step 2: Calculate *Beta value* using the below equation:

$$B = \sum\sum \frac{(Xij-Wij)}{(Xij-Wij)+(Zij-Yij)} \Big/ Num \tag{14}$$

Step 3: Calculate fuzzy earliest time (FET) for each node with the help of the equation given below:

$$FET_j = FET_i + AFT_{ij} \tag{15}$$

Step 4: At the intersection, node compare fuzzy earliest time (FET_{js}) and select the maximum number for fuzzy earliest time (FET_j) for each node.

$$FET_j = max\{FET_i + AFT_{ij}$$

$$FET_j = \max\{(S_a, U_a, V_a, W_a), (S_b, U_b, V_b, W_b)\} \tag{16}$$

Step 4.1: Now, find the values of A_1 and A_2 by using the below equations:

$$A_1 = \min\{S_a, U_a, V_a, W_a, S_b, U_b, V_b, W_b) \tag{17}$$

$$A_2 = \max\{S_a, U_a, V_a, W_a, S_b, U_b, V_b, W_b) \tag{18}$$

Step 4.2: Calculate the values of R (S_a, U_a, V_a, W_a) and R (S_b, U_b, V_b, W_b) with the given below equations:

$$R(S_i, U_i, V_i, W_i,) = \beta[(W_i - A_1/(A_2 - A_1 - V + W) + (1-\beta)[1 - 1 - (A_2 - S_i)/(A_2 - A_1 + V_i - S_i)\} \tag{19}$$

Step 4.3: Select the fuzzy earliest time (FET_j) which is more significant after comparing the results of R(S_i, U_i, V_i, W_i)

Step 5: Find the fuzzy latest time (FLT) for each node by using the equation given below:

$$FLT_j = FET_k + AFT_{jk} \tag{20}$$

Step 6: Intersection nodes Compare the fuzzy latest time (FLT_{js}) and consider the minimum number as FLT_j for each node.

$$FLT_j = min\{FET_k - AFT_{jk}\}$$

$$FLT_j = min\{((S_a, U_a, V_a, W_a), (S_b, U_b, V_b, W_b)\} \tag{21}$$

Consider the sub-steps of *Step 4 as* same for *Step 6*.

Step 7: Calculate fuzzy slack time (FST) for each activity from the given equation below.

$$FST_{ij} = FLT_j - (FET_i + AFT_{ij}) \tag{22}$$

Step 8: From all the paths FCT will be calculated for each one, and the below equation can be used to calculate the FCT for the activities in the possible path node.

$$FCT(P_n) = \sum FST_{ij} \tag{23}$$

Step 9: Minimum number is selected after calculating the FCTs, and the path which has the lowest R-value is taken as a Critical Path.

$$FCT(P_n) = min\{FCT(P_{i)}|i = 1,2,3,4,\dots.n \quad (24)$$

Activities involved in the Fuzzy Critical Path Method (FCPM):

The TAPI gas pipeline activities were divided into two categories, one for pipeline construction and the other for the gas compression station. In this regard, the two major types of activities are presented below in Table 3 as per Oilscams (2018) and Stephanatos (2014):

Table 3. Activities for Gas Pipelines and gas compression stations

Gas pipelines activities (*Oilscams, 2018*)		Gas compression stations (*Stephanatos, 2014*)	
A	Approval of TAPI gas pipeline	L	Installation of gas compression stations
B	Survey & route design	M	Installation of filters
C	Order of gas pipelines	N	Fitting of suction valves
D	Hiring of workers	O	Fitting of control valves
E	Cleaning & grading of ground for gas pipeline	P	Attachment to the gas pipeline.
F	Trenching of the ground		
G	Stringing & bending of gas pipeline		
H	Welding		
I	Non-destructive & hydrostatic testing		
J	Commissioning		
K	Restoration		

4.3. Genetic Algorithm

Genetic Algorithm (G.A.) is widely used in operations research (and also in computer sciences) for optimization related problems. The main idea behind (G.A.) is based on the theory of the Evolution of Darwin (Mitchell, 1996). The process by its nature is imperative in which a candidate solution with its properties is selected from the population, and this candidate can be "mutated" or "altered" to a new solution called generation; this process is continued till the final solution.

We aim to use the G.A. solution for the optimization of the material and transportation costs of the project. It may be noted that the work on the optimization of material and transportation cost has already been performed by many researchers using other techniques like Linear Programming and Time window constraints (Yadav & Kumar, 2017). However, for the construction of the gas pipeline, G.A. can quickly solve problems with vast data. Furthermore, the G.A. approach has been widely applied in optimizing the gas pipelines to optimize the design cost. For instance, Goldberg & Richardson (1987) used the Genetic Algorithm to optimize the working of a steady-state gas pipeline, which had 10 compressor stations and ten pipes. Each compression station consisted of 4 pumps in series (Goldberg & Richardson, 1987). The study's target is to optimize power consumption at specified controlled and allowable pressure (Goldberg & Richardson, 1987). Similarly, Singh & Nain (2012) designed a new model based on a Genetic Algorithm for selecting the pipe sizes. Some other studies based on genetic algorithm includes Goldberg, (1989) and Narváez, (2003).

This study's optimization model uses the non-dominated sorting genetic algorithm to minimize project costs as given by Equation (25).

$$Minimized\ cost = \sum_{m=1}^{n} Cost \quad (25)$$

The Genetic Algorithm procedure is applied using the following steps.

Step 1: Choose the type of optimization. The optimization can be single-objective optimization or multiple objective optimizations.

Step 2: Input the population size. The population size tells us the number of times it will run the different solutions. Therefore, the greater the population size, the more time the program will take to run.

Step 3: Choose the type of algorithm. Choose the type of Algorithm from Generational, Generational Elitist, and Steady State.

Step 4: Choose the respective crossover. This operator is used to connect individuals to produce new offspring's having characteristics of their parents. These offspring may have a better solution or a worse solution.

Step 5: Choose the selector. Selector plays an essential role in a genetic algorithm, which is how the algorithm will select solutions. There are three types of selectors used: Roulette, Roulette by Rank, and Tournament.

Step 6: Select the mutator. The mutation operator provides new genetic material during optimization. It has three types: Simple, Simple by Gene, and Adaptive Mutation.

Step 7: Defining chromosomes and linking with MS Excel. All decision variables for the problem give us genes in a genetic algorithm. The genes are comprehended together to form new chromosomes.

Step 8: Defining the objectives. One objective must be defined in a single objective and more than one for multiple-objective function.

Step 9: Define the constraints. Constraints are used to penalize variables for going out of ranges.

Step 10: Run the program. The study used a Microsoft excel add-in tool called SolveXL. This tool uses a genetic algorithm to solve complex problems. The optimization and configuration of the tool are done easily by a build-in user-friendly Wizard. Solve is superior to other commercial products and helps in performing single and multiple objective genetic algorithmic solutions. SolveXL utilizes a COM interface to interact with Microsoft Excel. SolveXL is written in the C++ programming language.

4.4. Data Collection

The data for this study was obtained both from primary and secondary sources. We used three questionnaires for getting the preliminary data required for analysis. These questionnaires were containing structured questions with pre-decided close-ended answers (such as multiple choice and rating scales). The data was collected using Google online survey tool. The data were obtained from 15 experts from the field. All the respondents were experts in the oil and gas industry. The respondents were managers and engineers working in the field for a long period. There were ten factors considered (as given in Table 4), and experts were asked to assign weights to each of these criteria using the four options (Very low, low, medium, high, and very high) as per their experience and knowledge. The data were obtained from all experts for both projects on all these ten factors.

Table 4. Factors consider and the weight assigned by experts

Criterion	IPI	TAPI
Capacity (C1) Gas Price (C2) Transit Fee (C3) Capital Cost (C4) Economic Factors (C5) Length of Pipeline (C6) Power Generation (C7) Time of Completion (C8) Geographical Location (C9) International Support (C10)	Very Low Low Medium-High Very High	Very Low Low Medium High Very High

The data collected through this procedure were more feasible, simpler, and time-efficient. This primary data was used in the usage of Fuzzy CPM and Fuzzy TOPSIS. However, there are many limitations, as many assumptions are made while finding out optimized costs and completion times. The exact duration of activities is not always reliable or sometimes even known (Rao & Nowpada, 2012). But given the uncertain situation and absence of enough published information, this approach was considered appropriate.

The secondary data were also used in this study. For instance, the cost of containers for different length pipes was obtained by consulting an expert field Engineer in Schlumberger. The criterion for Fuzzy TOPSIS was selected based on previous literature confirmed by the same field engineer. We took costing data available on the internet and from experts' opinions as the costing reports of both projects are not published. Parameters can be varied to find out total costs like elevation in the setup of pipelines, temperature, and any accident happening while working as it could cause a change in our Fuzzy CPM values. However, given these limitations, we still believe that it is the best approach to compare these two projects in given uncertain circumstances, where these projects have been under discussion for so long, but still, no significant progress has been made on either of them.

5. Results and Discussion

The result section is divided into three sub-section. These sections represent the results of Fuzzy TOPSIS, Fuzzy Critical Path method and the Genetic Algorithm, respectively. It may be noted that discussion on each of these results is also included in each of these specific sections, respectively.

5.1. Results from Fuzzy TOPSIS

The fuzzy TOPSIS method was applied using the expert ratings being obtained through the steps stated in the earlier section. Table 5 presents the final results of the Fuzzy TOPSIS method.[2]

There are several important observations from Table 5. It is clear that the IPI has an advantage over the TAPI in terms of power generation, transportation cost, transits fee, and gas prices. Furthermore, the *closeness coefficients* (determined using Equation (11)) for IPI and TAPI projects are 0.45299 and 0.43973, respectively. This implies that IPI is better than TAPI in the ranking (IPI > TAPI) in the considered study settings. This implies that the IPI project is ranked higher than the TAPI project.

Table 5. Results of Fuzzy TOPSIS

	IPI		TAPI	
	D Steric	D Negative	D Steric	D Negative
Gas Price	0.046	0.057	0.350	0.046
Transit Fee	0.499	0.367	0.310	0.498
Capital Cost	0.035	0.026	0.353	0.035
Economic factor	0.615	0.272	0.367	0.615
Length of Pipeline	0.045	0.033	0.348	0.045
Power Generation	0.629	0.951	0.371	0.630
Time Completion	0.049	0.086	0.349	0.049
Geographical Location	1.131	0.523	0.626	1.129
International Support	0.049	0.068	0.338	0.049
Capacity	0.033	0.075	0.365	0.033
	Sum of Li +	Sum of Li -	Sum of Li +	Sum of Li -
	3.130	2.457	3.777	3.128
CC (%)	43.973%		45.299%	

These findings are consistent with earlier studies such as Hudaa & Ali (2017) and Munir et al. (2013). These findings may not be unexpected given that with lower cost of gas, lesser security and safety concerns, no third country for transit, and higher supplier indicates better economic choices for IPI compared to TAPI. The major hurdle for IPI implementation is the Iran economic sanctions and the international geopolitical conditions.

[2] We do not include the detailed calculation results of this or other methods to keep the article's length to a manageable level. For interested readers, the detailed tables of the calculations can be provided on the request.

5.2. Fuzzy CPM

As stated earlier, there is significant progress going on TAPI compared to the IPI pipeline project. Therefore, this study undertakes the Fuzzy CPM analysis for identifying the critical activities associated with the TAPI pipeline project. In this regard, Table 6 shows various activities involved in the TAPI gas pipeline, predecessor, and fuzzy time for each activity. These time estimations are based on the experts' survey (also known as trapezoidal fuzzy numbers).[3] The Activity on Arrow (AOA) network is presented in Figure 3. The fuzzy activity time is shown in the form of trapezoidal fuzzy numbers, where a represents the minimum value, and d represents the maximum value.

The network diagram for this study is constructed based on the concept of Activity on Arrow. Figure 3 illustrates the AOA network diagram that is built using activities and their predecessors given in Table 6. Each circle represents a node while the alphabets are showing the activities between the nodes. The dotted lines in Figure 3 represent the dummy activities. The fuzzy time for the dummy activities is considered to be zero making the overall connection between the activities logically correct.

Table 7 shows all considered possible paths from the network diagram and calculated the fuzzy completion time using Equation (23). Subsequently, values of R are calculated for each path using Equation (24) and selected. The minimum value obtained was our critical path for the TAPI gas pipeline project.

Also, Table 8 presents the fuzzy earliest time, fuzzy latest time, and fuzzy slack time (FST) for each node, respectively. The result shows the TAPI gas pipeline project's critical path is (1-2-3-5-6-8-10-12-14-15-16-17-18) possible path, and the activities lying on the critical path are (A-B-D-E-F-G-H-I-J-K). This implies that the activities (A-B-D-E-F-G-H-I-J-K) cannot be delayed. Any delay in critical activity will automatically delay the entire TAPI pipeline project. However, other activities such as (L-M-N-O-P) can be delayed, as they do not lie on a critical path.

Project completion time for the TAPI gas pipeline was calculated by adding up the time duration of all activities on the critical path. The results show that the TAPI gas pipeline will take approximately 75 to 330.5 weeks to complete. However, this time is not consistent with a project of similar nature (Malaysian *Peninsula Gas Utilization* that was constructed in 1984 and is 1700 km long) that was completed in 517.43 weeks. The inconsistency in completion times may be because of many reasons, for instance, the improvement in technology during all these years and not considering all factors involved in the construction of the TAPI gas pipeline. Furthermore, the estimated time from *Peninsula Gas Utilization* is not optimized for the construction. The estimated time for the TAPI pipeline project is determined by Fuzzy CPM and is optimized for completion time.

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[3] The network diagram is the graphical representation of the project's activities, and it is constructed based on the activities predecessors. Generally, two types of network diagrams can be built: Activity on Arrow network diagram and Activity on Node network diagram.

Table 6. Activity fuzzy time for each activity of the TAPI gas pipeline

Activity	Predecessor	Activity fuzzy time AFT (in weeks)			
		a	b	c	d
A	-	48	52	63	70
B	A	9	13	15	20
C	B	2	3	4.5	6
D	B	4.5	5	5.5	7
E	B, D	3.5	5	6	8
F	D,E	5	6	9	12
G	C,F	3	7	8	8.5
H	G	5	6	7.5	9
I	G,H	3	4.5	8	10
J	I	1	1.5	2	3
K	J	1	2	2.5	3
L	C	3	5	7	9
M	L	4	6	8	9
N	M	3	4.5	5.5	7
O	N	2	3.5	5	6
P	O	3	5	6.5	9

Table 7. Fuzzy completion time (FCT_{pi}) and $R(FCT_{pi})$ values for all possible critical paths of the gas pipeline

Possible paths	Fuzzy completion time FCT (Pi)			R-value	
(1-2-3-4-7-9-11-13-18)	-535	-160.5	270.5	652.5	0.516
(1-2-3-5-6-8-10-12-14-15-16-17-18)	-877.5	-318.5	318.5	877.5	0.486
(1-2-3-6-8-10-12-15-16-17-18)	-742.5	-269.5	269.5	742.5	0.488
(1-2-3-4-10-12-14-15-16-17-18)	-728	-257.5	279.5	751.5	0.493
(1-2-3-5-8-10-12-14-15-16-17-18)	-810	-294	294	810	0.487
X_1=min(all possible paths)	-877.5	*Rmin*		0.485955	
X_2=max(all possible paths)	877.5				
Beta risk factor	0.473				
1-*Beta*	0.528				

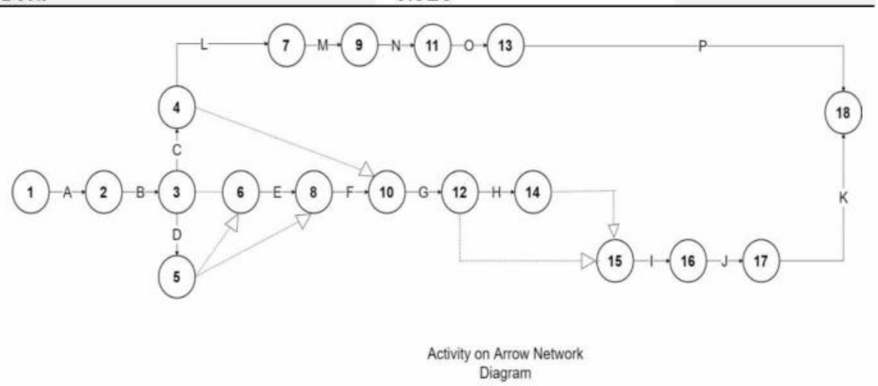

Figure 3 Activity on Arrow Network Diagram of TAPI pipeline project

Table 8. Fuzzy earliest time, fuzzy latest time and fuzzy slack time for each node

Node	Fuzzy earliest time (FET)				Fuzzy latest time (FLT)				Fuzzy slack time (FST)			
	a	b	c	d	a	b	c	d	a	b	c	d
1	0	0	0	0	-68	-25	24.5	67.5	-67.5	-25	25	68
2	48	52	63	70	2.5	38.5	76.5	116	-67.5	-25	25	68
3	57	65	78	90	22.5	53.5	89.5	125	-67.5	-25	25	68
4	59	68	82.5	96	43	70	103	136	-53	-13	35	77
5	61.5	70	83.5	97	29.5	59	94.5	129	-67.5	-25	25	68
6	61.5	70	83.5	97	29.5	59	94.5	129	-67.5	-25	25	68
7	62	73	89.5	105	52	77	108	139	-53	-13	35	77
8	65	75	89.5	105	37.5	65	99.5	133	-67.5	-25	25	68
9	66	79	97.5	114	61	85	114	143	-53	-13	35	77
10	70	81	98.5	117	49.5	74	106	138	-67.5	-25	25	68
11	69	83.5	103	121	68	90.5	118	146	-53	-13	35	77
12	73	88	106.5	125.5	58	82	113	141	-67.5	-25	25	68
13	71	87	108	127	74	95.5	122	148	-53	-13	35	77
14	78	94	114	134.5	67	89.5	119	146	-67.5	-25	25	68
15	78	94	114	134.5	67	89.5	119	146	-67.5	-25	25	68
16	81	98.5	122	144.5	77	97.5	123	149	-67.5	-25	25	68
17	82	100	124	147.5	80	99.5	125	150	-67.5	-25	25	68
18	83	102	126.5	150.5	83	102	127	151	-67.5	-25	25	68

5.3. Genetic Algorithm (G.A.)

This study also optimizes the material and transportation costs involved in the TAPI project using a Genetic Algorithm. In the absence of any number, we will develop a model that, if adopted, the project engineers can optimize the TAPI project's transportation and material costs. We used the Chelpipe firm's data (a Russian Company responsible for supplying pipes to the TAPI gas pipeline project). It is learned that Chelpipe provides customers with different packages giving them discounts as customers buy more containers, as shown in Table 9:

Table 9 Different packages along with their prices for each container

		Quantity Pricing (millions)				
		Length				
Packages	# of Pipeline Containers	1 meter	3 meters	5 meters	7 meters	12 meters
Package A	3	$ 4.50	$ 4.41	$ 4.28	$ 4.19	$ 3.96
Package B	5	$ 7.35	$ 7.20	$ 6.98	$ 6.83	$ 6.45
Package C	12	$ 17.10	$ 16.74	$ 16.20	$ 15.84	$ 14.94
Package D	15	$ 20.25	$ 19.80	$ 19.13	$ 18.68	$ 17.55
Package E	20	$ 24.00	$ 23.40	$ 22.50	$ 21.90	$ 20.40

The diameter of all the pipes is 1.42 meters. The cost values are taken by consulting experts in the oil and gas sectors. The first column in Table 9 shows different Packages, while the second column indicates the number of Containers in that Package. The remaining columns show the price of one meter, 3 meters, 5 meters, 7 meters, and 12 meters containers. For example, by analysis of *Package A* consisting of 3 Pipeline containers, a 1-meter pipe container costs $4.50 million, 3 meters pipe container costs $4.41 million, and a 5 meters pipe container costs $ 4.19 million, and 12 meters pipeline containers cost $ 3.69 million. The difference in prices is due to the weight secured by each container. The cost of 12 meters container is less because most of the container's space will go to waste as the 12 meters pipes are more in length, therefore weighing less and occupying more space. However, a 1-meter pipe takes more space in the container, increasing its weight as more 1-meter pipes can be brought by stacking. This increases the cost of one container of 1-meter pipeline container. The idea is to get the required number of containers at the most minimal cost.

This study optimizes the cost of purchasing 512 containers, which is the value taken *randomly* just to illustrate our model. Table 10 below discusses the number of Packages needed to satisfy the requirement of 512 containers at the cost of $562.43 million. The number of times G.A. will run the program is demonstrated by the population which was configured before running the algorithm. The more the population size, the more time it takes to find an optimized solution.[4] By the analysis of results, it can be determined that eight extra containers are required, which results in more cost. Therefore, if the number of iterations increases, the solution moves toward global value. Like the results achieved, a genetic algorithm can be used to construct models for different parameters like the pipeline material, and pipeline length can be added to further increase accuracy.

Table 10. Optimized cost model by genetic algorithm

Packages	Number of Packages	Total number of Containers for each packages	Per Unit Cost	Total Cost
A	5	15	$4.28	$21.38
B	1	5	$7.35	$7.35
C	0	0	$0.00	$0.00
D	0	0	$0.00	$0.00
E	25	500	$20.40	$510.00
Total cost=$ PKR 538.73 million; Required Containers= 512; Total Containers from calculation: 520				

The results demonstrated in Table 10 can act like a typical model for minimizing cost if several companies provide different packages, rather than using sophisticated techniques like the heuristic approach and integer programming approach for cost minimization. The model illustrated above can help engineers optimize *the TAPI gas pipeline's material* and *transportation* cost using the above model. Furthermore, the model allows engineers to achieve prices close to the global solution by increasing the number of iterations.

[4] We used a population size of 20; the genetic algorithm results can be presented on request for interested readers.

6. Conclusion

The study is based on the feasibility comparison of the IPI and TAPI projects. As Pakistan's energy demand is on the rise and there is a considerable supply-demand gap, these projects are essential for Pakistan's future energy needs. The study used a fuzzy set-based TOPSIS (a fuzzy MCDM) model to compare the two models and concluded that IPI is more beneficial to Pakistan than TAPI. Furthermore, since more work is ongoing on TAPI rather than on IPI, the study applied the Fuzzy Critical Path Method on the TAPI project to identify the project's critical activities. Finally, the Genetic Algorithm application is applied to a scenario for the TAPI gas pipeline that could be easily extended to a more realistic situation to optimize the material and transportation cost. The approach can help with the reduction of the material and transportation cost significantly.

There are several implications of this study. For instance, Pakistan is focused on TAPI mainly, whereas IPI is the project it must consider based on power generation capacity, transportation cost, transit fee and gas prices comparison of both projects. Therefore, this study recommends that the decision-makers in Pakistan explore the IPI project, especially in the recent geopolitical development. Because China also became a significant buyer from Iran. There are some reports of China showing interest in the IPI project (Pradhan, 2020). Pakistan may work on bringing China on board for this project; this will help meet China's energy demand for the future and make the IPI project economically more beneficial for Pakistan. The participation of China can help to nullify the global pressure against this project. Similarly, the study identifies the approximate time of accomplishing the TAPI gas project as about 75 to 330.5 weeks. These are useful information for policymakers working on the TAPI projects at the national level. Furthermore, the approach of this study can be adapted by the policymakers for comparing such projects globally.

The study is based on MCDM analysis and sample size does not matter much for such studies, however, it would have been better to have a sample from experts across multiple countries except only from Pakistan. This would have enriched the analysis. Some other factors such as consideration of Afghanistan under Taliban (as of 2021) may pose a big challenge for prospects of TAPI. Future studies on these projects must give due consideration to the “government” in Afghanistan as it would greatly influence the successful execution of the TAPI project.

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CELL PHONE RELATED VIOLATIONS AND MOTORCYCLE ACCIDENTS: A BAYESIAN APPROACH

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Research paper

Abstract: *The effects of cell phone use on motorcycle riders' behaviour are studied in smart city, Bhubaneswar, capital of state odisha, India. Most of motorcycle riders confess using cell phone devices while driving. Moreover, relationship between near miss and accidents has been found with the use of cell phone, reflecting a risk factor for motorcycle riders. This study examines the relationship between such type of behaviours, comprising calling and manipulating the screen, and the frequency of near miss and actual accidents among motorcycle riders. We conducted a web based survey measuring cell phone-specific violations, human errors, near miss and accident to motorcycle riders (N=289; age range; 18-60).We hypothesized that the relationship between cell phone use and near miss would be explained by an increase in the number of human errors committed, thus increasing the likelihood of being involved in near miss. Moreover, we hypothesized that near miss will predict actual accidents. Outcomes of path analysis showed that cell phone-specific violations predicted accidents throughout their consecutive effects on human errors and near miss only in the subsample of men. These findings offer an explanation of how cell phone use contributes to increase the likelihood of getting involved in near miss and actual accidents. The current study builds a path model explaining how cell phone-specific violations lead to more near miss among motorcycle riders.*

Key words: *cell phone-specific violations; human errors; near miss; accidents; motorcycle riders safety*

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1. Introduction

Motorcycles are a popular means of transport worldwide, although they can serve different purposes in different world regions. In high-income countries, they are often used for leisure or recreation, whereas they are commonly used for transporting people and goods in low- and middle-income countries (Organization for Economic Cooperation and Development/International Transport Forum, 2015). Most motorcycles in high-income countries are high-powered (over 250 cc), representing over 50% of the motorcycles fleet in North American and European countries compared to 5% in Southeast Asia (WHO, 2017). Within Southeast Asia, the proportion of motorcycle fatalities is much higher in Vietnam, Malaysia, Cambodia, and Thailand, at 58, 58, 70, and 73%, respectively (Abdul Manan et al., 2013; Ngo et al., 2012; WHO, 2015). Since 2010, the proportion of motorcycle fatalities has remained stable in most world regions (WHO, 2015), suggesting that motorcycle accidents continue to be a global safety issue. Among a number of factors contributing to motorcycle accidents, risk-taking behaviours have been found to be an important contributor (Lin & Kraus, 2009). Thus, there has been a growing body of literature investigating risky riding behaviours of motorcycle riders in high-income countries (Moskal et al., 2012; Stephens et al., 2017) as well as in low- and middle-income countries (Roehler et al., 2015; Tongklao et al., 2016; Vu & Shimizu, 2007).

For example, in a study in Hanoi, Vietnam, Vu & Shimizu, (2007) found that habits and intentions were strong predictors of risk-taking behaviours such as speeding, running red lights, and reckless overtaking. A study in Malaysia reported a high prevalence of street racing under the influence of alcohol and stunt riding (Wong, 2011). In Indonesia, Susilo et al. (2015) found that young adults and students were more likely to violate traffic regulations while examining a range of traffic violations among motorcycle riders Though cell phone use while driving a car has been a subject of much research (Backer-Grndahl & Sagberg, 2011; Beck & Watters, 2016; Harrison, 2011; Ismeik et al., 2015; McEvoy et al., 2005; Zhou et al,. 2012), mobile phone use while riding a motorcycle has only been investigated in recent research. It was observed that the prevalence of cell phone use while riding in 3 Mexican cities was 0.64% (Perez-Nunez et al., 2013) compared to 8.66% in Hanoi, Vietnam (Truong et al.,2016). Self-reported prevalence of cell phone use while riding, at any time rather than a specific time of observation, was much higher. About 40% of high school students in Vientiane, Laos (Phommachanh et al., 2017), and nearly 81% of university students in Hanoi and Ho Chi Minh City reported using a mobile phone while riding a motorcycle (Truong et al., 2017). Effects of gender, risk perceptions, and social networks on cell phone use while riding have also been highlighted (De Gruyter et al., 2017; Truong et al., 2017,Long et al.,2019). Cell phone use while riding can also be affected by situational factors. (Truong et al.,2016).

The high prevalence of cellphone use while motorcycle riders reported in previous research conveys a clear message about the generalized presence of such practices.

2. Literature Review

A number of studies have further explored associations between risk-taking behaviours and crash involvement given their importance to the identification of interventions and priorities. Using French crash data, Moskal et al. (2012) found that bike riders who were males, did not wear a helmet, or exceeded the alcohol concentration limit had a higher risk of being involved in a crash." In a survey of motorcycle riders in New South Wales, Australia, Stephens et al. (2017) showed that riders performing stunt behaviours and speed violations were more likely to be involved in a accident and close-accident, respectively. "According to a study of schoolchildren in India, tailgating and aggressive attitudes toward other motorcycle riders were associated with accident involvement" (Rathinam et al., 2007). "It was found in Taipei, Taiwan, that female motorcycle riders or riders with a higher tendency to engage in risky riding behaviours were more likely to be involved in a accident (Chang & Yeh,2007). A recent study in France suggested that female riders were less likely to be involved in injured accidents and particularly fatal accidents, however (Coquelet et al., 2018). In a study of fatal motorcycle accidents in Cambodia, Roehler et al. (2015) identified that speeding and drink riding were major contributing factors to motorcycle fatalities. A study of risky behaviours among students in Thailand reported that not wearing a helmet, speeding, and riding under the influence of alcohol were associated with motorcycle injuries (Tongklao et al., 2016).

Though the associations between a range of risk-taking behaviours and motorcycle accident involvement have been extensively investigated, little is understood about accident involvement among motorcycle riders who use a cell phone while riding. This understanding is particularly important in regions such as Southeast Asia where motorcycling is the dominant transport mode coupled with high prevalence of cell phone use while riding" (Phommachanh et al., 2017; Truong et al., 2017). "To address the research gap, this article investigates crash involvement and severity among motorcycle riders with risky riding behaviours, particularly cell phone use while riding. Data from a survey of university students' risky riding behaviours in Vietnam are utilized for the investigation because Vietnam has bike-dominated traffic (NTSC 2015; WHO, 2015) and young adults are more likely to engage in risky riding behaviours (Chang & Yeh, 2007; Truong et al.,2016).Traditionally, traffic accidents have been associated with human, road, environmental and vehicle factors (Bucsuházy et al., 2020). Human behaviour has been reported as the main contributing factor in 95% of bike accidents (Petridou & Moustaki, 2000; Sheykhfard et al., 2020).

In Vietnam, motorcycles contribute to around 95% of over 43 million registered vehicles and the vast majority of motorcycle are powered with an engine of less than 150 cc (NTSC, 2015; WHO,2017). Motorcycle riding is particularly important for mobility of young adults; most young adults aged 21–30 years old (58–77%) possess a motorcycle (Tran, 2013) and many students (40%) use one for travel to university (Ohmori et al., 2011). In 2014, Vietnam had over 25,000 reported traffic accidents and about 9,000 fatalities (NTSC, 2015). Motorcycle riders were involved in more than 70% of traffic accidents (Hung et al., 2008; Truong et al., 2016) and contributed to about 58% of traffic fatalities (Ngo et al., 2012). Traffic regulations in Vietnam specify penalties for risky riding behaviours such as not wearing a helmet, speeding, drink riding, running red lights, and using a cell phone or portable music device while riding. However, though helmet use has been well reported (Hung et al., 2008;Marco et al.,2019), little information is available about the compliance levels for other risk-taking behaviours.

According to the previous definitions, cellphone behaviors on the motorcycles can be considered violations given that, even if not all the countries' road rules officially ban them, they are deliberate deviations of the safe practice. All in all, even though the body of research on motorcycle riders' cellphone use is growing, there is need for more research on motorcycle riders to further untangle how–and to what extent – this type of violations affects human error because use of motorcycles (two wheelers) is very high in Bhubaneswar.

Based on the previously reported findings and the stated need for more research, we establish a hypothesized path model in which cellphone -specific violations will be positively associated with human errors (Hypothesis 1) and near miss (hypothesis 2). We also hypothesize that errors will be positively associated with near near miss (Hypothesis 3).To address this research gap, we hypothesized that close accidents will predict actual accidents (Hypothesis 4).

In a nutshell, we have hypothesized a model (see Figure 1) in which cellphone-specific violations and human errors predict near miss. In turn, near miss were hypothesized to predict actual accidents. Thus, we have posed that cellphone specific violations and human errors will indirectly increase the likelihood of actual accidents by raising the likelihood of occurrence of near miss. Therefore, we hypothesize that near miss will mediate the effect of cellphone-specific violations and human errors on actual accidents (Hypothesis 5). Moreover, we have also proposed that cellphone-specific violations will enhance the probability of committing human errors, and this at the same time will increase the likelihood of being involved in near miss." In addition, since we have also posed that accidents will be predicted by near miss, we hypothesize a serial mediation model in which human errors will mediate the effect of cellphone-specific violations on near miss, and these will act as a mediator between human errors and the occurrence of accidents (Hypothesis 6). "Figure 1 displays the hypothesized path model. Hypothesis 5 encompasses all the paths between cell phone-specific violations and accidents (i.e., those of H1, H2, H3, and H4), whereas Hypothesis 6 includes those between human errors and accidents (i.e., those of H3 and H4).

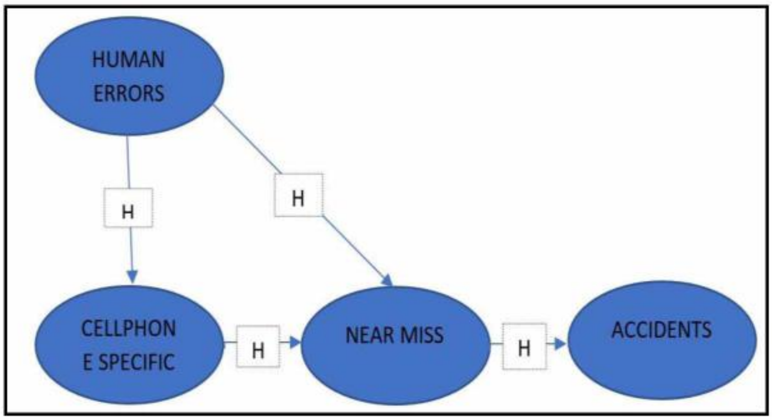

Figure 1. Conceptual Model of the Study (Hypothesized path model)

3. Methodology

Data were collected from October15, 2019 to December 30, 2019 through a self-reported online questionnaire at Bhubaneswar, Capital of Odisha, India. To reach a wide variety of participants with different demographics characteristics and from different locations in Bhubaneswar, the questionnaire was disseminated through the web. We found the motorcycle riders associations' websites and social media groups. Social media groups with fewer than 500 participants were discarded. We contacted in total 40 groups and 25 websites. To reach the selected targets two methods were used: (a) firstly, the link to the questionnaire was directly posted on groups' walls or on websites bulletin boards if available; (b) secondly, an email was written to the website administrators, kindly asking to advertise the questionnaire directly on their website, through their social media channels or inside their newsletter.

3.1 Descriptive Statistics

A total of 462 participants responded the questionnaire. After considering only those participants that had filled out the items for age, sex, and acknowledged to use the motorcycle at least once a week, the remaining sample comprised 289 (62.5%) participants. From these, 175 (60.5%) were male, 114 (39.4%) were female. The age of the participants ranged from age 18 to 60 years. The mean for female was 36.08 (*SD* = 14.42), the mean for male was 44.20 (*SD* 13.83), whereas the general mean value was 41.56 (*SD*= 14.42).

Among these participants, 31 (10.7%) of them used the motorcycle once a week, 31 (10.7%) used it twice, other 34 (11.6%) participants using motorcycles three times a week, 30 (10.3%) did so four times, 42 (14.5%) of them used motorcycles five times a week, and the remaining 121 (41.8%) participants used the motorcycles six or more times per week. Moreover, regarding the frequency of use in comparison with other means of transportation, 48.2% of the participants reported to use the motorcycles as a primary mode of transportation.

3.1.1. Cell phone specific violations."

To measure cell phone -specific violations, we used a 5-item self-reported scale based on Chataway et al.(2014) scale on distracted used motorcycles. We asked participants to state the perceived frequency with which they undertook behaviours, such as checking the phone while using motorcycles or texting messages. The frequency was expressed by using a 5-point Likert-type scale (ranging from 1=*never to 5=always;* assuming that "always" entails "as long as there is the possibility to do so" and not "continuously and all the time"). "Table 1 shows the item and subscale structure of the questionnaire, as well as some descriptive and reliability values.

Table 1. Descriptive statistics of the unsafe motorcycle rider behaviours.

Subscales	*M*	*SD*	Med	α
Cell phone-specific violations				0.880
Use a Cell phone to look for information or itineraries on the Internet.	1.52	0.87	1	
Use a Cell phone to send text messages.	1.43	0.82	1	
Use a Cell phone to read text messages.	1.62	0.86	1	
Use the Cell phone to respond a call.	1.95	0.98	2	
Use the Cell phone to call someone.	1.78	0.96	1	
Human Errors				0.672
Abruptly brake in order to avoid/dodge a vehicle.	2.59	0.92	3	
Abruptly swerve to avoid a bus or truck that turns right.	1.72	0.85	2	
Be grazed or hit by a cycle.	1.08	0.34	1	
Almost hit a pedestrian while you were turning right.	1.52	0.75	1	
Not sight a vehicle merging from a next street.	1.94	0.74	2	
Realize late that you have neglected a traffic red light.	1.34	0.62	1	
Doubt about who has preference in a roundabout.	1.34	0.68	1	

3.1.2. Human Errors.

To measure errors, we administered a 7-item scale based on those featured in the Driver Behavior Questionnaire (DBQ) (Sakashita et al., 2014) and the Adolescent motorcycling Behavior Questionnaire (AMBQ) (De Waard et al., 2014), adapting the former ones to the context of cycling. This scale had been previously used by Puchades et al.(2018). The items asked participants to state the frequency with which they undertook such behaviors by using a 5-point Likert-type scale (ranging from 1= *never* to 5=*always*). Table 1 shows the seven items and subscale structure of the questionnaire, as well as some descriptive and reliability values.

3.1.3. Near miss and accidents.

To obtain a measure of near miss and accidents, we used two items. Regarding the item measuring near miss: 'In this past year, have you been about to get involved in an accident (either with other road users or a single accident) while you were using your motorcycle?' (0=no, it never happened to me, 1=once, 2=twice, 3= three times, 4=four or more). The item measuring accidents was 'In your whole life, have you ever had an accident (either with other road users or a single crash) while you were driving your motorcycle?' (1=No, it never happened to me, 2=Yes, but I did not get hurt, 3=Yes, I got injured and I went to emergency services to get checked, 4=Yes, I got injured and after being checked I got hospitalized). To finally obtain three categories, the last two replies were merged into one category that represented accidents involving injuries.

4. Statistical analysis

SPSS version 23 and analysis of a moment structures(AMOS) were used for statistical analysis. Different stages were adopted for analysis of the data. First, correlation coefficients among the key variables were calculated. The magnitude of effect sizes of correlation coefficients was evaluated according to Cohen's (1988) guidelines for interpreting the magnitude of correlation coefficients." Specifically, correlation coefficients of .10 are "small," correlation coefficients of .30 are "medium," and correlation coefficients of .50 are "large" in terms of magnitude of effect sizes. "Second, we employed path analysis to test mediations, as well as direct effects, because it allowed us to estimate a model that constrains several direct effects to zero (e.g., an eventual direct effect of cell phone -specific violations on accidents, thereby, letting us test our hypotheses without the need of testing a saturated model (Hayes, 2013)."Provided that two endogenous variables of our model (i.e., near miss and accidents) are ordinal, we applied Bayesian estimation, AMOS' approach to addressing ordered-categorical data in SEM models (Byrne, 2010; Skrondal & Rabe-Hesketh, 2005).

5. Results

The participants that had not been involved in any motorcycle accident were 112 (38.7%), whereas 106 (36.6%) suffered at least one accident but did not get injured, and 81 (28.0%) of them had been involved in a motorcycle accident in which they got injured." The number of participants that had not suffered a near miss was 103 (35.3%), and 72 (24.9%) of them had indeed been involved in one. "Of those that had been involved in more than one close accidents, 44 (15.2%) participants had suffered two, 28 (9.6%) three, and 42 (14.5%) of them suffered four or more.

Ten (3.4%) cases had at least one missing value, and 12 (4.0%) values were missing among all the variables measured. Since the percentage of missing values is not higher of 5%, it can be considered as irrelevant (Schafer, 1999). Table 1 displays the subscale items of the unsafe motorcycle rider behaviors questionnaire along with their Mean and Standard Deviation values." As it can be seen, the cellphone -specific violation and human error reported as most frequent were "Use the cellphone to respond a call" and "Abruptly break in order to avoid/dodge a vehicle," respectively. Computation of Cronbach alpha has been done for all items by using the reliability command of SPSS software and its value are reflected in Table-1.

5.1. Unsafe motorcycle riding behaviours effect on near miss and accidents

Table 2 displays the Spearman bivariate correlations between the key variables studied as well as the descriptive statistics. We employed Spearman's rho due after the Shapiro–Wilk test results suggested the non-normal distribution (i.e., $p < .001$) of all the variables in the model. Human errors correlated with cellphone-specific violations ($p < 0.01$) and with near miss ($p < 0.01$). This allows us to continue to test the hypothesized model.

Table 2. Descriptive statistics and variable intercorrelations

Factors	M	SD	Range	1	2	3	4
1. Human errors	1.64	0.42	1–5	–	0.19^{**}	0.31^{**}	0.00
2. Cellphone-specific violations	1.63	0.75	1–5		-	0.05	0
3. near miss	1.33	1.38	–			-	24^{**}
4. Accidents	0.81	0.76	–				-

"*Note*:*Correlations are significant at $p < 0.05$ (2-tailed),

**Correlations are significant at $p < 0.01$ (2-tailed).

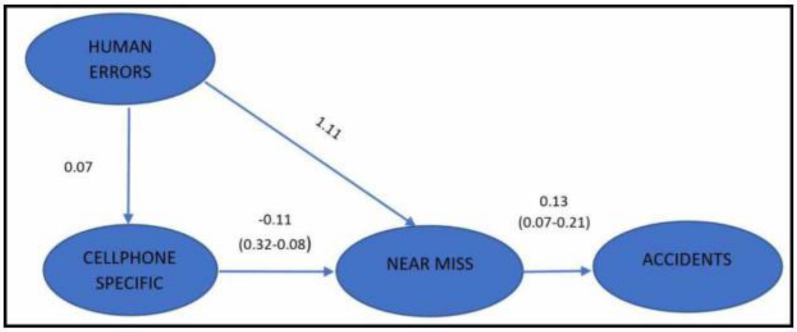

Figure 2. Path model with Bayesian estimates

Regarding the hypothesised model, Figure 2 shows the Bayesian estimates for each path. Cell phone -specific violations predicted human errors (Hypothesis 1) but not near miss (Hypothesis 2), whereas human errors did predict near miss (Hypothesis 3). In turn, near miss predicted actual accidents (Hypothesis 4). Mediation analysis showed that close accidents were mediating the effect of human errors on accidents (Bayesian estimate = 0.085, 95% confidence interval [CI] [0.043, 0.134]; Hypothesis 5). Furthermore, cell phone-specific violations predicted accidents throughout its consecutive effects on human errors and near miss (Bayesian estimate=0.013, 95% CI [0.003, 0.026]; Hypothesis 6).

We performed a gender comparison of the path model and found differences between males and females. The subsamples of male and female participants were of 175 and 114 participants, respectively. Whereas the path estimates found in the general sample were confirmed for the subsample of male participants, we found that in the female subsample, cell phone-specific violations did not predict human errors (Bayesian estimate=.043, 95% CI [0.055, 0.144]), and near miss did not predict accidents (Bayesian estimate=.100, 95% CI [0.013, 0.213]). Moreover, we also found that the estimate of the path between human errors and near miss is lower for females Bayesian estimate=.672, 95% CI [0.181, 1.155]) than for males (Bayesian estimate= 1.583, 95% CI [1.051, 2.112]). We give possible explanations for this in the discussion.

6. Discussion

The objectives of the current study were to examine the impact of cellphone-specific violations and human errors on the likelihood of near miss as well as the indirect effect of such behaviors on actual accidents among motorcycle riders. Moreover, it also aimed to unveil any gender differences in the relationships between the unsafe behaviors"(i.e., cellphone-specific violations and human errors) and the hazardous outcomes (i.e., close accidents and accidents).

It is important to note that, differently from previous studies, our findings focused on cellphone -specific violations as a distinct type of violation, whereas other research had differentiated between more common and exceptional violations (e.g., Feenstra et al., 2011). The rationale for this was that, as previously explained, such type of violations was thought to increase error occurrence by its effect on visual detection and perception. In addition, we wanted to examine whether such behaviors were indeed predicting human errors and near miss or, due to eventual compensatory behaviors (Goldenbeld et al., 2012) they were not associated.

Path analyses confirmed all the hypotheses except for Hypothesis 2, that is, cellphone-specific violations did not directly predict near miss. Nevertheless, it did predict human errors (Hypothesis 1) in the general sample, thus bringing about the point that cellphone-specific violations may indeed involve more unsafe behaviors dependent on information processing, instead of leading to more compensatory behaviors. Nevertheless, there is still the need to explore whether this relationship between cellphone-specific violations and errors is also due to a confounding variable such as motorcycle rider's safety concerns. This way, motorcycle riders less concerned about safety could be committing more human errors and using more frequently the cellphone while motorcycle riding. Errors predicted near miss, and these, accidents. Our data only partially supported Hypothesis 5 because there was no direct effect from cellphone -specific violations on near miss, impeding an indirect effect of the former on accidents unless considering the role of human errors.

Moreover, the results confirm a mediation effect proposed in Hypothesis 6, which explains the effect of cellphone-specific violations on accidents throughout human errors and near miss. These findings differ from those of Feenstra et al. (2011) according to which human errors and violations (common and exceptional) were directly predicting near miss. In our study, only human errors predicted near miss frequency. Moreover, they found exceptional violations to predict accident severity and human errors to predict accident frequency, whereas we did not find significant correlations between any unsafe motorcycle riding behaviors (i.e., human errors and cellphone -specific violations) and accidents. Twisk et al. (2015) found errors, but not violations themselves, to predict accidents, thus concurring with our findings. Nevertheless, it is worth noting main differences between these previous studies and our research. We conducted the study among adults and not adolescents, thus, age differences could be explaining some of the differences in findings.

Moreover, we have found gender differences in the effects of cellphone-specific violations on errors and that of near miss on accidents. That is, the results found in the general sample were confirmed for men, whereas cellphone-specific violations did not predict human errors and neither near miss did predict accidents in the female subsample." Cellphone-specific violations not predicting human errors in the female subsample could be due to gender differences in perception and attention."We offer two possible sets of explanations next: one theoretical and another one concerning statistical artefact. On the one hand, previous research in psychology of individual differences has found that women are quicker in identifying and discriminating objects visually, have a wider peripheral vision, and are more likely to estimate situations as risky (Ellis et al., 2008). Moreover, Feenstra et al. (2011) found that boys tended to engage in riskier behaviors, thus suggesting that women might adopt a less risky approach to motorcycle riding and, therefore, might undertake compensatory behaviors while committing cellphone-specific violations. This could diminish the effect of using cellphone while motorcycle riding on the human errors committed. A possible explanation for the fact that near miss did not predict accidents in the female subsample can be found in the smaller prediction of near miss by human errors. This can be interpreted as near miss being more dependent on variables other than human error in women. Thus, the frequency of hazardous outcomes such as near miss, and accidents by extension, is not related to human error, perhaps due to women's eventual less risky approach to motorcycle riding derived from their higher likelihood of estimating a situation as risky in comparison to men (Ellis et al., 2008).

It is important to note that, differently from previous studies, our findings focused on cell phone-specific violations as a distinct type of violation, whereas other research had differentiated between more common and exceptional violations (e.g., Feenstra et al., 2011). The rationale for this was that, as previously explained, such type of violations was thought to increase error occurrence by its effect on visual detection and perception. In addition, we wanted to examine whether such behaviours were indeed predicting errors and near miss or, due to eventual compensatory behaviours (Goldenbeld et al., 2012) they were not associated.

Fewer risk-taking behaviors could be reducing the motorcycle riders' own influence on their accident frequency, leaving it up to other road users' behaviors, and therefore conditioning the occurrence of near miss and accidents to eventual and more random encounters with other distracted or irresponsible road users. On the other hand, a possible explanation to the lack of association in the female subsample could be due to a lack of statistical power provided a not big enough subsample size. Even though there is no single answer about whether a sample is large enough to conduct SEM, a common rule of thumb is that there should be 20 observations per parameter that needs to be estimated in the model (Kline, 2016). Therefore, with 12 parameters to be estimated in our model, both subsample sizes are too small to obtain adequate statistical power. Thus, not finding an association between cellphone -specific violations and human errors, and near miss and accidents could be due to the relatively small subsample size. Thus, more research with bigger samples is needed to clarify whether these differences exist or are due to statistical artefact.

7. Limitations

There are some limitations to this study. On the one hand, we used a self-reported questionnaire to measure unsafe motorcycle rider behaviors and safety outcomes (i.e., near miss and accidents). This entails two limitations: (1) memories of accidents and near miss (e.g., Chapman & Underwood, 2000), as well as those of unsafe behaviors that do not depend on conscious control (i.e., errors), may not be accurate according to previous findings (Bradburn et al., 1987; Twisk et al., 2015)." Previous research suggests that an estimated 80% of the near miss may be forgotten after 2 weeks of the event (Chapman & Underwood, 2000). "Moreover, (2) common method variance (CMV), which refers to the amount of variance attributable to the use of the same method to measure related variables (Podsakoff et al.,2003), constitutes a limitation to our study given that we measured all the variables using self-reported questionnaires. On the other hand, online surveys advertised on websites might involve self-selection bias and, therefore, the resulting sample might not be representative of the whole population of motorcycle rider.

8. Conclusion

This research has numerous societal and practical implications from which we have concluded regarding future research needs. Cellphone -specific violations is introduced in the model and conceptualized them as a type of violation that is affecting the occurrence of unsafe behaviors relying on human errors in men, but not in women. "Furthermore, for men, we have found them to anticipate near miss and accidents through an indirect effect. This entails that cellphone-specific violations might have an effect on other unsafe behaviors and, therefore, offers a broader understanding of how such behaviors end up leading to eventual accidents. That nevertheless, there might be some confounding variables that could explain the effect of cellphone-specific violations on human errors such as motorcycle rider's safety concerns.

Our findings suggest that cellphone -specific violations appear to contribute to the frequency of errors while motorcycle riding among men. Furthermore, both human errors and cellphone-specific violations predict accidents throughout an indirect effect on near miss. Finally, these findings contribute to examine possible gender factors that can moderate the relationship between unsafe motorcycle riding behaviours and accident risk.

In conclusion, this study has highlighted a number of relationship between near miss and accidents by motorcycle riders, in particular the use of cell phones while riding. The findings suggest a number of key challenges for road safety in Bhubaneswar, India, not least the relatively high rate of accident involvement associated with cell phone use while riding a motorcycle. Addressing these challenges is an important task given the dominance of motorcycle use in Bhubaneswar, India and their increasing numbers each year.

The findings of this study provide solid evidence on safety issues of cell phone use while riding a motorcycle, which should be utilized in educational programs and publicity campaigns. Given the relatively high near miss and accidents associated with this behaviour, stronger police enforcement efforts should also be prioritized. Despite some limitations, the study still provides a significant contribution to understanding cell phone related specific violations in developing countries by helping decision-makers to define safety strategies to minimize motorcycle riders' near miss and accidents. In further stages of this research, a survey could be conducted to validate its findings. Using mixed-methods analysis is also recommended for comparing various results and providing valuable lessons on developing a more sophisticated framework. Apart from various factors, some prominent factors like individual and environmental factors may be considered for future research.

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CONTROL OF NON-INSTANTANEOUS DEGRADING INVENTORY UNDER TRADE CREDIT AND PARTIAL BACKLOGGING

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Abstract: *Inventory management is an extremely difficult task. It has become usual practice for a provider during the last few decades to provide a retailer with a credit term. In this article, a non-instantly degradable product inventory system is built with a price-sensitive demand and a Weibull credit term allocation reduction rate. Some backlogged deficiencies are permitted. The aim is to maximize the total profit by taking three cases into account. Numerical examples, graphical representations and sensitivity analysis demonstrate the application of the approach developed in this study.*

Key words: *Inventory control, Weibull deterioration, price-sensitive demand, trade credit, non-instantaneous deterioration.*

1. Introduction

Everyday life is a prevalent phenomenon in the deterioration of commodities. Some examples of these things are vegetables, fruits, dairy products, drugs and blood bank. Therefore, the tendency of the object to deteriorate is important to take into account. In the real world, most products have a shelf life that allows them to maintain their quality or their original condition for a period of time. During that period of time, there was no deterioration in the situation. Examples of such foods include vegetables and fruits as well as meat, fish, and seafood. This is referred to as "non-instantaneous deterioration" in the scientific literature. First and foremost, Ghare and Schrader (1963) took an important stride in this approach. Giri et al. (2003) have presented a mathematical methodology for Weibull decreasing items. Ghosh and Chaudhury (2004), as well as Roy and Chaudhuri (2009), proposed inventory systems for perishable commodities that are in low supply. Das et al. (2010) created A model for

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an item with variable quality that takes into account random machine failure. An inventory model for small lots was developed by Das et al. (2011), with regular and overtime works being combined to produce the production rates. Kawale and Bansode (2012) developed an inventory system for perishable items under the influence of time dependent holding cost using Weibull rate of deterioration. Barik et al. (2013) created a mathematical approach for deteriorating items under the influence of inflation. Confident weights of experts were used by Das et al. (2014) as part of an algorithmic method for MAGDM problems. In this topic, For m secondary warehouses (SWs) and one primary warehouse, Das et al. (2015) created a multi-item multi-warehouse inventory model for degrading goods. Mahata et al. (2018) and Muriana (2020) also offered several models. Ghosh et al. (2021) studied an EOQ model with full backorder for perishable commodities with varied advance and delayed payment conditions. Non-instantaneous models were investigated by Ouyang et al. (2006) and Wu et al. (2009). Soni (2013) used trade credit to overcome the problem of non-instantaneously decaying inventories (Table 1).

Table 1. Literature summary

Authors	Price dependent demand	Deterio ration	Trade Credit	Constant Holding Cost	Non-Instantaneous
Giri et al. (2003)	No	Yes	No	No	No
Ghosh and Chaudhury (2004)	No	Yes	No	Yes	No
Roy and Chaudhuri (2009)	No	Yes	No	Yes	No
Jain and Kumar (2010)	No	Yes	No	Yes	No
Geetha and Udayakumar (2016)	Yes	Yes	No	Yes	Yes
Mahata et al. (2018)	No	Yes	Yes	Yes	No
Singh et al. (2020)	No	Yes	Yes	Yes	No
Halim et al. (2021)	Yes	Yes	No	Yes	No
Present Paper	Yes	Yes	Yes	Yes	Yes

Geetha and Udayakumar (2016) employed advertisement dependent demand, Shaikh and Cárdenas-Barrón (2020), and Udayakumar et al. (2020) developed alternative inventory models for non-instantaneous falling commodities. Models in this direction have also been presented by Ahmad and Benkherouf (2018) and Tripathi and Pandey (2020). Ouyang et al. (2006) introduced a price-dependent inventory system. Goyal and Chang (2009) used stock-based demand to construct inventory policy. Amutha and Chandrasekaran (2013) created an inventory system for perishable items that incorporates the Weibull rate of deterioration and price-based demand. Avinadav et al. (2013), Guchhai et al. (2013), Avinadav et al. (2014), Feng et al. (2017), and Cheng et al. (2020) followed the work. Halim et al. (2021) devised a strategy for resolving an inventory problem involving decaying products. Sana et al. (2008) developed an inventory model with advertising cost and selling price dependent demand using trade credit. Sarkar (2012) also provided an inventory system for deteriorated commodities purchased on trade credit. By assuming two-level trade credits, Shah et al. (2015) pioneered a novel methodology. Several academics, including Aggarwal and Jaggi (2017), Goyal (2017), and Shah et al. (2017), created several approaches to address inventory problems while taking trade credit into account. Tripathi and Chaudhary (2017) and Singh et al. (2020) employed the

Weibull deterioration rate to develop distinct inventory models for perishable products with trade credits. Tripathi et al. (2018) suggested mathematical systems with various trade credits. Sundararajan et al. investigated the impact of trade credit under inflation on an EOQ model (2020). Jain and Kumar (2010) created a strategy for perishable items with Weibull deterioration rates and scarcity. Sarkar and Sarkar (2013) improved a partial backlog solution approach for time-dependent perishable commodities. Mishra (2016) and Gupta et al. (2018) employed partial backlogging to generate multiple systems for Weibull degrading goods. Jamal et al. (2017), San-José et al. (2018), Akbar et al. (2019), Rastogi and Singh (2019), and San-José et al. (2020) all made major contributions in this area.

Although several researchers have developed inventory models that take the Weibull deterioration rate into account in their work, practitioners have paid less attention to the inclusion of non-instantaneous deterioration. Novelties of present study are as follows:

- We focused our efforts on constructing a mathematical system for non-instantaneous Weibull declining products under trade credit.
- Demand is thought to be price related.
- Shortages are considered partially backlogged are tolerated.
- Impact of different input variables is studied.
- Concavity of profit functions is shown by graphs.

The structure of the paper is in the following format: Segment 2 of this article describes several notations and assumptions. Segment 3 discusses the model formulation. Segment 4 contains the solution technique. Segment 6 demonstrates concavity of profit functions. Segment 7 discusses sensitivity analysis. Segment 8 contains the conclusion.

2. Notations and Assumptions

To create the mathematical model, some notations and assumptions are used.

2.1 Notations

K	The ordering cost /order
Q	The retailer's order quantity
$D(p)$	The demand rate
m	The time in which the item does not decay
M	Permissible delay period
c	Purchasing price /unit
p	Selling price /unit
h	Unit holding price
s	Unit shortage cost/order
c_l	Lost sale cost/ unit

I_p	Rate of interest payable/dollar/unit time
I_e	Rate of interest earned/dollar/unit time
τ	The time at which the inventory level becomes zero
T	Replenishment period
$\theta(t)$	Deterioration rate
$I_1(t)$	Inventory level in period $0 \le t \le m$
$I_2(t)$	Inventory level in period $m \le t \le \tau$
$I_3(t)$	Inventory level in period $\tau \le t \le T$
$Z(\tau)$	Total profit
*	Optimal value

2.2 Assumptions

- The replenishment rate is assumed to be limitless.
- The time stamp begins at zero.
- Shortages that are partially backlogged are allowed. The pace of backlogging is determined by the time required for subsequent replenishing. As a result, during the stock-out period, it is denoted as $B(t) = e^{-\delta(T-t)}$, where $0 \le \delta \le 1$.
- Articles within the cycle period cannot be replaced or repaired in any way.
- The demand D depends on selling price p and $D(p) = \lambda p^{-\mu}$, $\lambda \ge 0, \mu \ge 0$.
- After the interval $[0, m]$ the goods begin to deteriorate with the Weibull deterioration rate, $\theta(t) = \alpha\beta t^{\beta-1}; \alpha \ge 0, \beta \ge 0$.
- For a specified term the supplier gives commercial credit to the retailer.

3. Mathematical Formulation

During the period $[0, m]$, there is no deterioration. The inventory level in the period $[m, \tau]$ is consumed by both demand and deterioration. In the period $[\tau, T]$, shortages occur which are partially backlogged.

The change of inventory level $I(t)$ in different time durations given by

$$\frac{dI_1(t)}{dt} = -\lambda p^{-\mu}, 0 \le t \le m \tag{1}$$

$$\frac{dI_2(t)}{dt} = -\lambda p^{-\mu} - \alpha\beta t^{\beta-1} I_2(t), m \le \tau \tag{2}$$

$$\frac{dI_3(t)}{dt} = -\lambda p^{-\mu} e^{-\delta(T-t)}, \tau \le t \le T \tag{3}$$

The solution of equations (1), (2), and (3) with boundary conditions $I_1(0) = Q, I_2(\tau) = 0 = I_3(\tau)$, are

$$I_1(t) = -\lambda p^{(-\mu)} t + Q. \tag{4}$$

$$I_2(t) = \lambda p^{-\mu}\left[(\tau - t) + \frac{\alpha}{\beta+1}\left(\tau^{\beta+1} - t^{\beta+1}\right) - \alpha t^{\beta}(\tau - t)\right]. \tag{5}$$

$$I_3(t) = \lambda p^{-\mu}(\tau - t)\left[1 - \delta T + \frac{\delta}{2}(\tau + t)\right]. \tag{6}$$

Using boundary conditions, $I_1(m) = I_2(m)$, $I_3(T) = -E$ we get

$$Q = \lambda p^{-\mu}\left[\tau + \frac{\alpha}{\beta+1}\left(\tau^{\beta+1} - m^{\beta+1}\right) - \alpha m^{\beta}(\tau - m)\right]. \tag{7}$$

$$E = \lambda p^{-\mu}(T - \tau)\left[1 - \delta T + \frac{\delta}{2}(\tau + T)\right] \tag{8}$$

The total annual profit/cycle is obtained by including the following:

1. Ordering cost (O) = K.
2. Inventory holding cost

(H) $= h\left\{\int_0^m I_1(t)dt + \int_m^\tau I_2(t)dt\right\}$

$$= h\left\{\begin{array}{l} \frac{\tau^{\beta+1}(\tau x_6 - x_4)}{x_1} - m^{\beta+1}\frac{(m x_6 - x_4)}{x_1} + \frac{x_2}{x_5}(\tau - m) \\ -\frac{\lambda m^2}{2p^{\mu}} - \frac{\lambda(1+\beta)}{x_3}\left(\tau^2 - m^2\right) - \frac{\alpha\lambda}{x_1}\left(\tau^{\beta+2} - m^{\beta+2}\right) \\ +\frac{m\lambda}{p^{\mu}}\left[\tau - \alpha m^{\beta}(\tau - m) + \frac{\alpha\left(\tau^{\beta+1} - m^{\beta+1}\right)}{\beta+1}\right] \end{array}\right\}$$

where

$x_1 = p^y(3b+2+b^2)$,
$x_2 = zx(1+b+az^b)$,
$x_3 = 2p^y(b+1)$,
$x_4 = zax(b+2)$,
$x_5 = p^y(b+1)$,
$x_6 = ax(b+1)$.

3. Purchase cost

$$(\text{P}) = c(Q-E)$$
$$= \frac{c\lambda}{p^\mu}\left[\frac{\alpha}{\beta+1}\left(\tau^{\beta+1}-m^{\beta+1}\right)-(\tau-m)\alpha m^\beta+T\left(\frac{T\delta}{2}-1\right)+\frac{\delta}{2}\tau^2-T\delta\tau\right].$$

4. Sales revenue

$$® = p\left\{\int_0^\tau D(p)dt+\int_\tau^T D(p)e^{-\delta(T-t)}dt\right\} = \frac{p\lambda}{p^\mu}\left[\tau-\frac{e^{-\delta(T-\tau)}-1}{\delta}\right].$$

5. Shortage cost

$$(\text{S}) = s\int_\tau^T -I_3(t)dt = \frac{s\lambda}{6p^\mu}(T-\tau)^2(2\delta\tau-2T\delta+3).$$

6. Lost sale cost

$$(\text{L}) = c_l\int_\tau^T D(p)\left(1-e^{-\delta(T-t)}\right)dt = \frac{\lambda c_l}{\delta p^\mu}\left(e^{-\delta(T-\tau)}-\delta\tau+T\delta-1\right).$$

7. Interest payable

(i) When $0 \le M \le m$

$$IP_1 = cI_p\left\{\int_M^m I_1(t)dt+\int_m^\tau I_2(t)dt\right\}$$

$$= cIp\left\{\begin{array}{l}\frac{\tau^{\beta+1}(\tau x_6-x_4)}{x_1}-m^{\beta+1}\frac{(mx_6-x_4)}{x_1}+\frac{x_2}{x_5}(\tau-m)\\ -\frac{\lambda(1+b)}{x_3}\left(\tau^2-m^2\right)-\frac{\alpha\lambda}{x_1}\left(\tau^{\beta+2}-m^{\beta+2}\right)\\ +\frac{\lambda}{2p^\mu}(M-m)\left[\begin{array}{l}M+m-2\tau-\\ 2\alpha m^\beta\tau-\frac{2\alpha\left(\tau^{\beta+1}+\beta m^{\beta+1}\right)}{\beta+1}\end{array}\right]\end{array}\right\}.$$

(ii) When $m \le M \le \tau$

$$IP_2 = cI_p\left\{\int_M^\tau I_1(t)dt\right\} = cIp\left\{\begin{array}{l}\frac{\tau^{\beta+1}(\tau x_6 - x_4)}{x_1} - m^{\beta+1}\frac{(mx_6 - x_4)}{x_1} - \frac{x_2}{x_5}(M-\tau)\\ +\frac{\lambda(1+b)}{x_3}(M^2-\tau^2) + \frac{\alpha\lambda}{x_1}(M^{\beta+2}-\tau^{\beta+2})\end{array}\right\}.$$

(iii) When $\tau \le M \le T$, $IP_3 = 0$.

8. Interest earned

(i) *When* $0 \le M \le m$

$$IE_1 = pI_e\int_0^M tD(p)dt = \frac{p\lambda}{2p^\mu} I_e M^2.$$

(ii) When $m \le M \le \tau$

$$IE_2 = pI_e\int_0^M tD(p)dt = \frac{p\lambda}{2p^\mu} I_e M^2.$$

(iii) When $\tau \le M \le T$

$$IE_3 = pI_e\left\{\int_0^\tau tD(p)dt + \int_0^\tau (M-\tau)D(p)dt\right\} = \frac{p\lambda\tau}{p^\mu} Ie\left(m - \frac{\tau}{2}\right).$$

The total profit/unit time $Z(\tau)$ is written as

$$Z(\tau) = \begin{cases} Z_1(\tau); 0 \le M \le m \\ Z_2(\tau); m \le M \le \tau \\ Z_3(\tau); \tau \le M \le T \end{cases}$$

$$Z_1(\tau) = \frac{R + IE_1 - O - P - H - S - L - IP_1}{T} = \frac{X_1}{T}. \tag{9}$$

Where

$$X_1 = \left(\frac{p\lambda}{p^\mu}\left[\tau - \frac{e^{-\delta(T-\tau)} - 1}{\delta}\right]\right) + \left(\frac{p\lambda}{2p^\mu} IeM^2\right) - (K)$$

$$-\left(\frac{c\lambda}{p^\mu}\left[\frac{\alpha}{\beta+1}\left(\tau^{\beta+1} - m^{\beta+1}\right) - (\tau - m)\alpha m^\beta + T\left(\frac{T\delta}{2} - 1\right) + \frac{\delta}{2}\tau^2 - T\delta\tau\right]\right)$$

$$-\left(h\left\{\begin{array}{l}\frac{\tau^{\beta+1}(\tau x_6 - x_4)}{x_1} - m^{\beta+1}\frac{(mx_6 - x_4)}{x_1} + \frac{x_2}{x_5}(\tau - m) - \frac{\lambda m^2}{2p^\mu}\\ -\frac{\lambda(1+\beta)}{x_3}\left(\tau^2 - m^2\right) - \frac{\alpha\lambda}{x_1}\left(\tau^{\beta+2} - m^{\beta+2}\right)\\ +\frac{m\lambda}{p^\mu}\left[\tau - \alpha m^\beta(\tau - m) + \frac{\alpha\left(\tau^{\beta+1} - m^{\beta+1}\right)}{\beta+1}\right]\end{array}\right\}\right)$$

$$-\left(\frac{s\lambda}{6p^{\mu}}(T-\tau)^2(2\delta\tau-2T\delta+3)\right)-\left(\frac{\lambda c_l}{\delta p^{\mu}}\left(e^{-\delta(T-\tau)}-\delta\tau+T\delta-1\right)\right)$$

$$-\left(cIp\left\{\begin{array}{l}\frac{\tau^{\beta+1}(\tau x_6-x_4)}{x_1}-m^{\beta+1}\frac{(mx_6-x_4)}{x_1}+\frac{x_2}{x_5}(\tau-m)\\ -\frac{\lambda(1+b)}{x_3}\left(\tau^2-m^2\right)-\frac{\alpha\lambda}{x_1}\left(\tau^{\beta+2}-m^{\beta+2}\right)\\ +\frac{\lambda}{2p^{\mu}}(M-m)\left[\begin{array}{l}M+m-2\tau-2\alpha m^{\beta}\tau\\ -\frac{2\alpha\left(\tau^{\beta+1}+\beta m^{\beta+1}\right)}{\beta+1}\end{array}\right]\end{array}\right\}\right)$$

$$Z_2(\tau)=\frac{R+IE_2-O-P-H-S-L-IP_2}{T}=\frac{X_2}{T}. \qquad (10)$$

Where

$$X_2=\left(\frac{p\lambda}{p^{\mu}}\left[\tau-\frac{e^{-\delta(T-\tau)}-1}{\delta}\right]\right)+\left(\frac{p\lambda}{2p^{\mu}}IeM^2\right)$$

$$-(K)-\left(\frac{c\lambda}{p^{\mu}}\left[\begin{array}{l}\frac{\alpha}{\beta+1}\left(\tau^{\beta+1}-m^{\beta+1}\right)-(\tau-m)\alpha m^{\beta}\\ +T\left(\frac{T\delta}{2}-1\right)+\frac{\delta}{2}\tau^2-T\delta\tau\end{array}\right]\right)$$

$$-\left(h\left\{\begin{array}{l}\frac{\tau^{\beta+1}(\tau x_6-x_4)}{x_1}-m^{\beta+1}\frac{(mx_6-x_4)}{x_1}+\frac{x_2}{x_5}(\tau-m)\\ -\frac{\lambda m^2}{2p^{\mu}}-\frac{\lambda(1+\beta)}{x_1}\left(\tau^2-m^2\right)-\frac{\alpha\lambda}{x_1}\left(\tau^{\beta+2}-m^{\beta+2}\right)\\ +\frac{m\lambda}{p^{\mu}}\left[\tau-\alpha m^{\beta}(\tau-m)+\frac{\alpha\left(\tau^{\beta+1}-m^{\beta+1}\right)}{\beta+1}\right]\end{array}\right\}\right)$$

$$-\left(\frac{s\lambda}{6p^{\mu}}(T-\tau)^2(2\delta\tau-2T\delta+3)\right)$$

$$-\left(\frac{\lambda c_l}{\delta p^{\mu}}\left(e^{-\delta(T-\tau)}-\delta\tau+T\delta-1\right)\right)$$

$$-\left(cIp \left\{ \begin{array}{l} \frac{\tau^{\beta+1}(\tau x_6 - x_4)}{x_1} - m^{\beta+1}\frac{(mx_6 - x_4)}{x_1} - \frac{x_2}{x_5}(M-\tau) \\ + \frac{\lambda(1+b)}{x_3}(M^2-\tau^2) + \frac{\alpha\lambda}{x_1}(M^{\beta+2}-\tau^{\beta+2}) \end{array} \right\} \right)$$

$$Z_3(\tau) = \frac{R + IE_3 - O - P - H - S - L - IP_3}{T} = \frac{X_3}{T}. \tag{11}$$

Where

$$X_3 = \left(\frac{p\lambda}{p^\mu}\left[\tau - \frac{e^{-\delta(T-\tau)} - 1}{\delta}\right]\right) + \left(\frac{p\lambda\tau}{p^\mu} Ie\left(m - \frac{\tau}{2}\right)\right)$$

$$-(K) - \left(\frac{c\lambda}{p^\mu} \left[\begin{array}{l} \frac{\alpha}{\beta+1}(\tau^{\beta+1} - m^{\beta+1}) - (\tau - m)\alpha m^\beta \\ + T\left(\frac{T\delta}{2} - 1\right) + \frac{\delta}{2}\tau^2 - T\delta\tau \end{array} \right] \right)$$

$$-\left(h \left\{ \begin{array}{l} \frac{\tau^{\beta+1}(\tau x_6 - x_4)}{x_1} - m^{\beta+1}\frac{(mx_6 - x_4)}{x_1} + \frac{x_2}{x_5}(\tau - m) \\ -\frac{\lambda m^2}{2p^\mu} - \frac{\lambda(1+\beta)}{x_3}(\tau^2 - m^2) - \frac{\alpha\lambda}{x_1}(\tau^{\beta+2} - m^{\beta+2}) \\ + \frac{m\lambda}{p^\mu}\left[\tau - \alpha m^\beta(\tau - m) + \frac{\alpha(\tau^{\beta+1} - m^{\beta+1})}{\beta+1}\right] \end{array} \right\} \right)$$

$$-\left(\frac{s\lambda}{6p^\mu}(T-\tau)^2(2\delta\tau - 2T\delta + 3) \right)$$

$$-\left(\frac{\lambda c_l}{\delta p^\mu}\left(e^{-\delta(T-\tau)} - \delta\tau + T\delta - 1\right) \right)$$

4. Solution Procedure

The aim of this article is to maximize total profit. The following condition must be fulfilled by $Z_i(\tau)$ for maximization:

$$\frac{dZ_i(\tau)}{d\tau} = 0, \; i = 1,2,3 \tag{12}$$

Solving the equation (12) for τ, we get optimal value τ^* of τ, for which $\frac{d^2 Z_i(\tau)}{d\tau}\Big|_{\tau=\tau^*} < 0 \quad ; i = 1,2,3$

5. Numerical Examples

Example 5.1

When $0 \le M \le m$

$K = 10000, h = 10, c = 20, p = 100, m = 0.08, M = 0.05, \alpha = 0.125,$
$\beta = 2, \lambda = 6000, \mu = 0.9, I_e = 0.20, I_p = 0.25, T = 1, \delta = .7, s = 60, c_l = 70$

Putting these values in equation (9), we obtain the optimal solutions

$\tau_1^* = 0.6924$

$Z_1^* = 2371$

$Q_1^* = 67.1094$

Example 5.2

When $m \le M \le \tau$

$K = 10000, h = 10, c = 20, p = 100, m = 0.05, M = 0.07, \alpha = 0.125,$
$\beta = 2, \lambda = 6000, \mu = 0.9, I_e = 0.20, I_p = 0.25, T = 1, \delta = .7, s = 60, c_l = 70$

Putting these values in equation (10), we obtain the optimal solutions

$\tau_2^* = 0.6930$

$Z_2^* = 2363.2$

$Q_2^* = 67.1989$

Example 5.3

When $\tau \le M \le T$

$K = 10000, h = 10, c = 20, p = 100, m = 0.05, M = 0.9, \alpha = 0.125,$
$\beta = 2, \lambda = 6000, \mu = 0.9, I_e = 0.20, I_p = 0.25, T = 1, \delta = .7, s = 60, c_l = 70$

Putting these values in equation (11), we obtain the optimal solutions

$\tau_3^* = 0.7335$

$Z_3^* = 1530$

$Q_3^* = 71.2940$

To solve the above examples, MATLAB software is used.

6. Concavity of Profit Functions

Figures 1, 2, and 3 depict the concavity of the profit functions, and this finding corresponds to the theoretical idea of a profit functions with concavity.

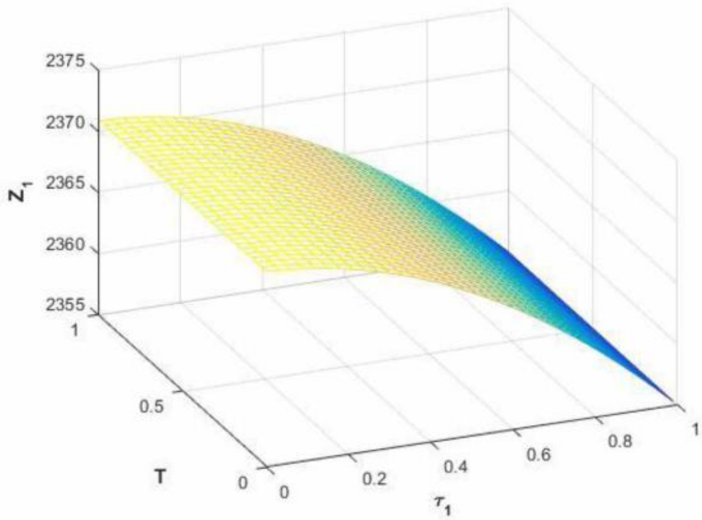

Figure 1. Concavity of profit function $Z_1(\tau)$

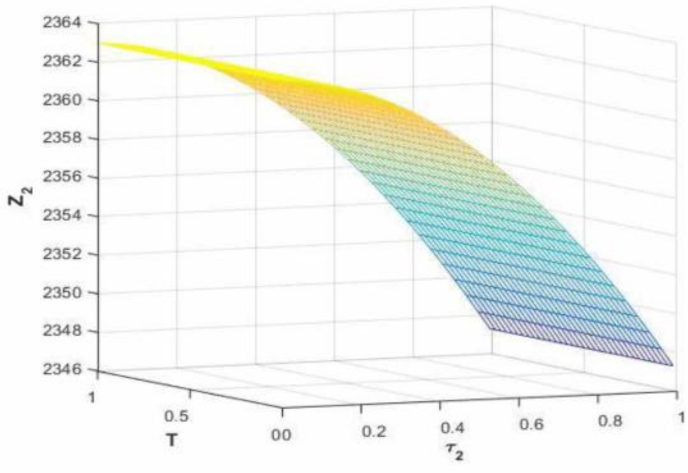

Figure 2. Concavity of profit function $Z_2(\tau)$

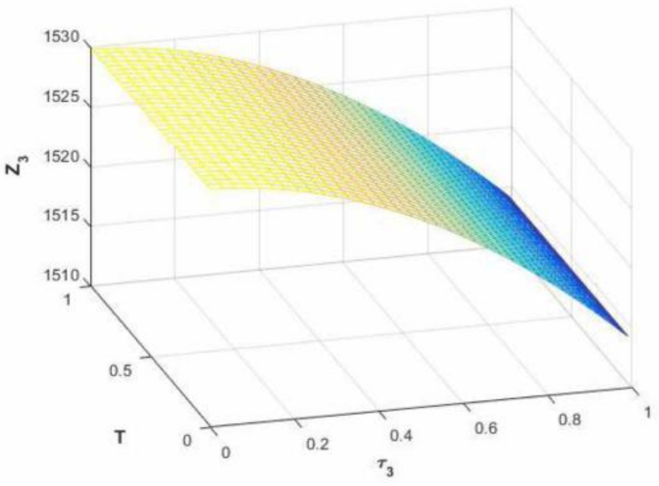

Figure 3. Concavity of profit function $Z_3(\tau)$

7. Sensitivity Analysis and Observations

For sensitivity analysis, we have used the preceding cases. The impacts of parameter modifications on optimal values of Z^*, τ^* and Q^* in this segment have been studied. The results are summarized in Tables 2, 3 and 4.

Observations and Managerial Implications

From Table 2, Table 3 and Table 4, we observe that

- As we increase the parameter h by 10% and 20% we observe that the total profit Z^* remains almost constant and the optimal values of τ^* and Q^* decrease. We can therefore suggest to the firm that they are free to accept any type of lot as long as the profit remains constant in accordance with the above parameters.
- Increasing the value of K by 10% and 20% increases the value of Z^* very rapidly but the optimal values of τ^* and Q^* decreases. In order to increase profits, a company will increase the value of K parameter.
- Enlarge of c by 10% and 20% results increase in Z^* and decrease in Q^* while it drops the value of τ^* very sharply. In order to increase profits, a company will increase the value of c parameter.
- When p increases by 10% and 20%, it makes a decrease in Z^* and an increase in τ^* but it causes the value of total inventory Q^* to drop very rapidly. In order to increase profits, a company will decrease the value of p parameter.

- When we increase the parameters s and c_l by 10% and 20% we see that the optimal values of τ^* and Q^* show the same behavior (they increase) while the total profit remains unchanged. We can therefore suggest to the firm that they are free to accept any type of lot as long as the profit remains constant in accordance with the above parameters. Figures 4, 5, and 6 demonstrate the effect of various factors on profit functions.

Table 2. Change in τ^*, Q_1^* and Z_1^* with respect to parameters

Parameters	%change in parameters	τ^*	Q_1^*	Z_1^*
h	-20	0.7013	68.0065	2323.9
	-10	0.6968	67.5528	2347.6
	+10	0.6881	66.6765	2394.1
	+20	0.6837	66.2338	2416.9
K	-20	0.6924	67.1094	371.041
	-10	0.6924	67.1094	1371.0
	+10	0.6924	67.1094	3371.0
	+20	0.6924	67.1094	4371.0
c	-20	0.7415	72.0749	2168.0
	-10	0.7169	69.5820	2274.3
	+10	0.6680	64.6568	2458.4
	+20	0.6437	62.2236	2536.6
p	-20	0.6668	78.8904	2922.2
	-10	0.6801	72.4239	2624.5
	+10	0.7037	62.6383	2151.2
	+20	0.7142	58.8202	1957.5
s	-20	0.6739	65.2490	2322.3
	-10	0.6834	66.2037	2347.3
	+10	0.7010	67.9762	2393.6
	+20	0.7092	68.8038	2415.0
c_l	-20	0.6749	65.3494	2327.7
	-10	0.6839	66.2539	2350.0
	+10	0.7004	67.9157	2391.1
	+20	0.7080	68.6826	2410.1

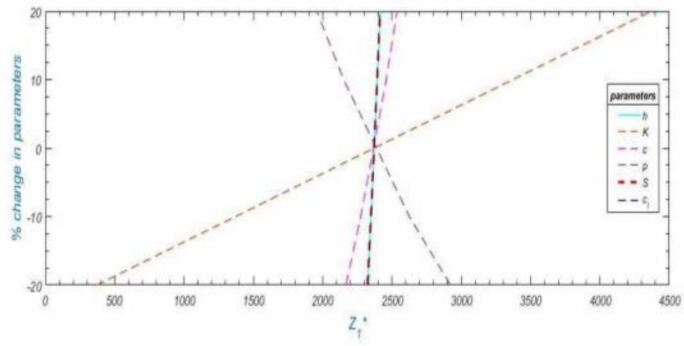

Figure 4. Changes in Z_1^* with respect to parameters

Table 3. Change in τ^*, Q_2^* and Z_2^* with respect to parameters

Parameters	%change In parameters	τ^*	Q_2^*	Z_2^*
h	-20	0.7018	68.0864	2316.0
	-10	0.6974	67.6425	2339.8
	+10	0.6886	66.7557	2386.4
	+20	0.6843	66.3228	2409.2
K	-20	0.6930	67.1989	363.2157
	-10	0.6930	67.1989	1363.2
	+10	0.6930	67.1989	3363.2
	+20	0.6930	67.1989	4363.2
c	-20	0.7420	72.1570	2161.0
	-10	0.7175	69.6729	2266.8
	+10	0.6686	64.7449	2450.3
	+20	0.6444	62.3204	2528.2
p	-20	0.6674	78.9980	2913.5
	-10	0.6807	72.5215	2616.3
	+10	0.7043	62.7211	2143.7
	+20	0.7148	58.8972	1950.3
s	-20	0.6745	65.3374	2314.6
	-10	0.6840	66.2926	2339.6
	+10	0.7016	68.0662	2385.7
	+20	0.7097	68.8842	2407.0
c_1	-20	0.6755	65.4379	2320.0
	-10	0.6845	66.3430	2342.2
	+10	0.7010	68.0056	2383.2
	+20	0.7086	68.7730	2402.1

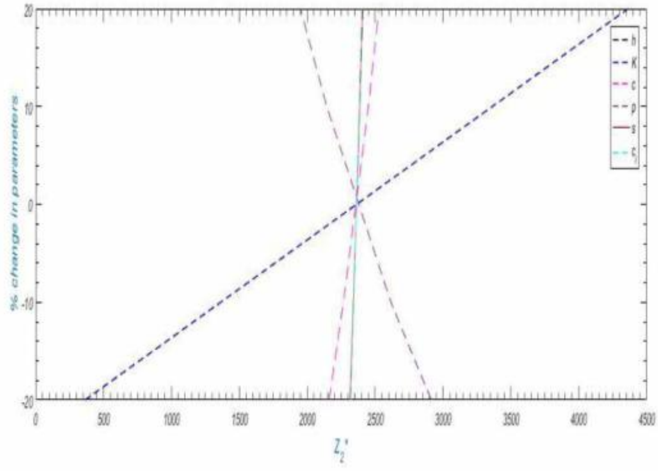

Figure 5. Changes in Z_2^* with respect to parameters

Table 4. Change in τ^*, Q_3^* and Z_3^* with respect to parameters

Parameters	%change In parameters	τ^*	Q_3^*	Z_3^*
h	-20	0.7418	72.1367	1477.1
	-10	0.7376	71.7101	1503.7
	+10	0.7294	70.8782	1556.0
	+20	0.7253	70.4626	1581.7
K	-20	0.7335	71.2940	-470.0094
	-10	0.7335	71.2940	529.9906
	+10	0.7335	71.2940	2530.0
	+20	0.7335	71.2940	3530.0
c	-20	0.7741	75.4279	1322.1
	-10	0.7538	73.3572	1429.7
	+10	0.7132	69.2379	1623.0
	+20	0.6930	67.1989	1708.8
p	-20	0.7092	84.1433	2092.8
	-10	0.7220	77.1037	1789.2
	+10	0.7440	66.4120	1304.7
	+20	0.7536	62.2385	1105.9
s	-20	0.7188	69.8044	1492.7
	-10	0.7263	70.5639	1511.8
	+10	0.7403	71.9843	1547.3
	+20	0.7469	72.6551	1563.8
c_1	-20	0.7200	69.9259	1497.3
	-10	0.7269	70.6247	1514.1
	+10	0.7398	71.9335	1545.2
	+20	0.7457	72.5331	1559.7

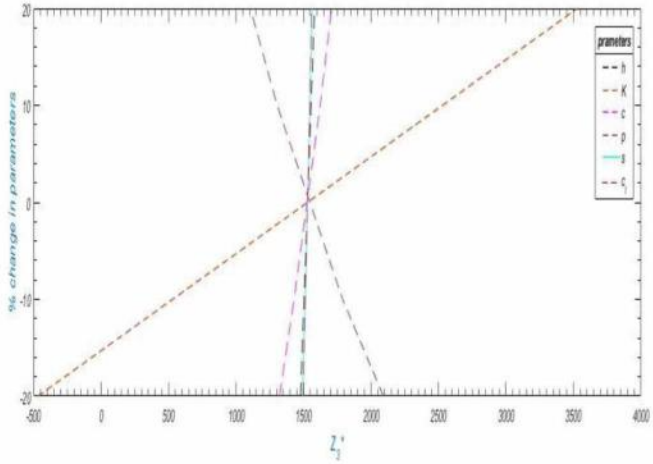

Figure 6. Changes in Z_3^* *with respect to parameters*

8. Conclusion and Future Scope

In present article Weibull rate of deterioration is influenced by trade credit and demand depends on selling price. The model is assessed with the variable time and optimized. Stagnant shortages are acceptable with backlogged allowances.

Numerical examples and sensitivity analysis illustrate the constructed model. Our findings demonstrate:

- Increasing holding cost increases the overall profit.
- The optimal overall profit grows as the shortage costs increase.

The supplied model can be used to keep inventory of things that do not perish quickly, such as electronic products, and fashion items. In retail trading, the approach is useful for optimizing unit time profit when partial backlogging occurs. Future work in this area will examine freight charges and other factors. This is also applicable when all the parameters are clear and precise, but if there is any uncertainty in the future, we can use fuzzy mathematics to deal with the situation.

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SCHEDULING WITH LOT STREAMING IN A TWO-MACHINE RE-ENTRANT FLOW SHOP

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Abstract: *Lot streaming is splitting a job-lot of identical items into several sublots (portions of a lot) that can be moved to the next machines upon completion so that operations on successive machines can be overlapped; hence, the overall performance of a multi-stage manufacturing environment can be improved. In this study, we consider a scheduling problem with lot streaming in a two-machine re-entrant flow shop in which each job-lot is processed first on Machine 1, then goes to Machine 2 for its second operation before it returns to the primary machine (either Machine 1 or Machine 2) for the third operation. For the two cases of the primary machine, both single-job and multi-job cases are studied independently. Optimal and near-optimal solution procedures are developed. Our objective is to minimize the makespan, which is the maximum completion time of the sublots and job lots in the single-job and multi-job cases, respectively. We prove that the single-job problem is optimally solved in polynomial-time regardless of whether the third operation is performed on Machine 1 or Machine 2. The multi-job problem is also optimally solvable in polynomial time when the third operation is performed on Machine 2. However, we prove that the multi-job problem is NP-hard when the third operation is performed on Machine 1. A global lower bound on the makespan and a simple heuristic algorithm are developed. Our computational experiment results reveal that our proposed heuristic algorithm provides optimal or near-optimal solutions in a very short time.*

Key words: *scheduling, lot streaming, two-machine, re-entrant flow shop, makespan.*

1. Introduction

Manufacturing systems vary from a simple one-stage environment to more complex environments, such as a general job shop system, where jobs have different routings through multiple stages. Since the well-known efficient scheduling algorithm for the basic two-machine flow shop system, in which the flow of each job

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is the same, was proposed by Johnson (1954), scheduling problems in different and more complicated manufacturing environments have been extensively studied. The ***re-entrant flow shop***, which is a relatively new flow shop manufacturing environment, has drawn researchers' attention. In the re-entrant flow shop, a job has to re-visit some of the machines since the number of operations for each job is more than the number of machines (Lev & Adiri, 1984). We observe re-entrant Re-entrant flow shops can be observed mainly in textile and high-tech industries, such as printing printed circuit boards, wafer fabrications, and signal processing.

In all of the studies in the literature for the re-entrant flow shops and most of the scheduling studies for the other multi-stage manufacturing systems, it is assumed that jobs are indivisible entities. Thus, an operation of a ***job-lot*** (i.e., a process batch) consisting of identical units must be finished before it this job lot is transferred to the next machine. However, in many industrial applications, a job lot can be split into several ***sublots*** (i.e., transfer batches), which are the partial batches of the process batch. Transfer of the processed sublots to downstream machines without waiting for the completion of the whole job-lot on a machine gives an opportunity of allows the operations overlapping to overlap. The process of simultaneously splitting a job-lot into sublots and scheduling those sublots by overlapping their operations is known as ***lot streaming***, which was first mentioned as a scheduling technique by Reither (1966).

In this paper, we consider a scheduling problem with lot streaming in a two-machine re-entrant flow shop where each job-lot is processed first on Machine 1, then goes to Machine 2 for its second operation before it returns to the primary machine (either Machine 1 or Machine 2) for the third operation. We first focus on the single-job problem where a job-lot is spilt split into a given number of consistent or variable sublots. ***Consistent sublots*** case is the case where the size of each sublot does not change over the machines. However, the sublot sizes may change vary over the machines when ***variable sublots*** are used. Next, we extend the problem to the multi-job case in which the size of sublots and the schedule of multiple sublots and job lots need to be determined simultaneously. Our objective is to minimize the makespan, equivalent to the time to complete the last sublot in the single-job case, whereas it is the time to complete the last job lot in the multi-job case. Makespan aims to increase the utilization of the machines in the shop. To the best of our knowledge, our study is the only one that applies lot streaming for single- and multi-job cases in the re-entrant flow shops.

The organization of the remaining parts is as follows. The following section presents a literature review on lot streaming problems, especially those in two- and three-machine manufacturing shops. In Section 3, the single-job problem is studied, and the optimal schedules with consistent and variable sublots are developed. Section 4 considers the multi-job lot streaming problem and gives an exact algorithm that determines the optimal consistent-sublot sizes and job schedules when the primary machine is Machine 2. Next, the multi-job lot streaming problem, in which the primary machine is Machine 1, is proved to be strongly NP-hard, and a polynomial-time solvable case of the problem is provided. Moreover, a heuristic algorithm is provided for the multi-job problem where the primary machine is Machine 1, and its effectiveness is computationally tested. Finally, our brief conclusions and some issues for future research are summarized in Section 5.

2. Literature review

Although lot steaming is known and used in practice, there were no analytical studies in the literature of scheduling problems until the late '80s. Since then, lot streaming has attracted significant interest from researchers dealing with scheduling problems.

Based on the number of job lots, the studies in the literature can be divided into two categories. One category is called the ***single-job lot problem*** and deals with the sublot-sizing problem in which the sublot sizes are determined when there is a single job lot. The other category is called ***multi-job problem*** and deals with the ***sublot-sizing*** and ***job-sequencing*** subproblems simultaneously. Here, we limit our literature review to the lot streaming studies for the single- and multi-job lot cases in two- and three-machine manufacturing shops only to expose the proper place of our study in the literature.

The study by Baker (1988) is the first one considering the lot streaming technique for a single-job problem in two- or three-machine flow shops to minimize the makespan. For the two-machine case, he provided a linear programming model and determined the sublot sizes optimally. He also determined the optimal sublot sizes for the three-machine case where the job-lot is split into two sublots only. Potts & Baker (1989) proved that optimal sublots are consistent in the two-machine flow shop and illustrated that the consistent sublots are not always optimal for the flow shops with three and more machines. Glass et al. (1994) developed an algorithm that determines the optimal consistent-sublot sizes for the three-machine flow shop to minimize the makespan. This study was extended to the cases with sequence-independent detached and attached setups by Chen & Steiner (1997) and Chen & Steiner (1998), respectively. In the ***attached setup*** case of a machine, the first sublot belonging to a job lot should be available before setting up this machine. However, in the ***detached setup*** case, no need to wait for the arrival of the job lot. In both cases, no setup is necessary between successive sublots of the same job lot. In both cases, no setup is necessary between successive sublots of the same job lot. On the other hand, variable sublots case of the single job-lot problem was first examined by Trietsch (1989). The optimal solution with variable sublots in the three-machine flow shop was proposed by Trietsch & Baker (1993). Alfieri et al. (2012) and Alfieri et al. (2021) proposed exact, and heuristic solution approaches based on dynamic programming for a single-job problem to minimize the makespan and total flow time, respectively, in a two-machine flow shop with attached setup times.

Vickson & Alfredson (1992) considered the concept of lot streaming for scheduling multiple job lots in flow shops. They demonstrated that a modified Johnson's algorithm with unit-sized sublots solves the two-machine makespan minimization problem when the number of sublots in each jot-lot is unlimited and proved that sublots in each job-lot should be processed successively without the intermingling of different job lots. Vickson & Alfredson's study was extended by Çetinkaya & Kayalıgil (1992) to develop a unified algorithm that treats sequence-independent attached and detached setups. Çetinkaya (1994) considered the scheduling of multiple job lots in a two-machine flow shop with attached setup and removal times on the machines and proved that the optimal schedule of the job lots to minimize the makespan is obtained by determining the equal or unequal sublots sizes of each job-lot independently and sequencing the job lots by a modified

Johnson's algorithm. Vickson (1995) provided an optimal solution for the multi-job problem in a two-machine flow shop with sequence-independent attached or detached setups and transfer times from the first machine to the second one. Pranzo (2004) extended Çetinkaya's study by considering limited buffers between machines. Glass & Possani (2011) considered the two-machine flow shop problem with attached setup and transportation times to minimize the makespan of the multiple job lots. Their study showed that sublot-sizing and job-sequencing problems are solved independently, as in Çetinkaya (1994) and Vickson (1995), and provided an algorithm solvable in polynomial time. Baker (1995) considered the multi-job problem with equal-sized sublots and setup times in a two-machine flow shop and proposed an algorithm using the time-lag approach. Yang & Chern (2000) extended Baker's study to where detached setup times, transportation times, and removal times exist. Sriskandarajah & Wagneur (1999) investigated the multi-job problem in a two-machine flow shop with no-wait constraint. Çetinkaya (2005) considered a two-machine flow shop with a single agent transferring a completed item from Machine 1 to Machine 2. Machine 1 is blocked while the transport agent is in transferring and returning. He provided an algorithm that determines the optimal schedule for the case with unit-sized sublots.

From the early 2000s, researchers began to consider flow shops with more than three machines (stages). Several metaheuristic algorithms, such as genetic algorithms (Yoon & Ventura, 2002; Marimuthu et al., 2008; Martin, 2009; Defersha & Chen, 2010), discrete particle swarm optimization algorithm (Tseng & Liao, 2008), threshold accepting and ant-colony optimization algorithms (Marimuthu et al., 2009), discrete artificial bee colony algorithm (Pan et al., 2011), and migrating birds optimization algorithm (Devendra et al., 2014; Meng et al., 2018) have been proposed to solve the multi-job lot streaming problem by considering its different aspects.

All the studies mentioned above for the multi-job scheduling with lot streaming in the flow shops with more than three machines assume that sublots in each job lot should be processed successively for each operation on each machine. i.e., the intermingling of the job lots is not allowed, and the schedules are permutation schedules where the sequence of job lots on all machines is the same. However, a more realistic case is when intermingling of the job lots and non-permutation schedules are allowed. Feldmann & Biskup (2008) investigated the permutation flowshop scheduling problem with lot streaming and intermingling and developed a mixed-integer programming model. Rossit et al. (2016) investigated this non-permutation flowshop scheduling problem with lot streaming. They proposed a mathematical model to minimize the makespan of the multiple job lots that are not allowed to be intermingled.

Besides the studies mentioned above, lot streaming studies for other two- and three-machine manufacturing shops are scarce. There are studies considering open shops (Şen & Benli, 1999), hybrid flow shops (Kim et al., 1997; Zhang et al., 2003; Zhang et al., 2005; Liu, 2008; Defersha, 2011; Defersha & Chen, 2012a; Naderi & Yazdani, 2015; Cheng et al., 2016; Zhang et al., 2017; Wang et al., 2019; Li et al., 2020), and mixed shops (Çetinkaya & Duman, 2010), job shops (Buscher & Shen, 2009; Defersha & Chen, 2012b), and assembly shops (Sarin et al., 2011; Yao & Sarin, 2014; Nejati et al., 2016; Cheng & Sarin, 2020).

The comprehensive surveys by Chang & Chiu (2005), Sarin & Jaiprakash (2007), Gomez-Gasquet et al. (2013), and Cheng et al. (2013), and Salazar-Moya & Garcia (2021) are also available for lot streaming problems with job lots having more than one operation in multiple machines environments.

As we can see from the lot streaming literature and to the best of our knowledge, there is no previous study dealing with lot streaming for single- and multi-job cases in the re-entrant flow shops. The main contributions of our study can be summarized as follows:

- This study is the first one in the scheduling literature dealing with lot streaming in the re-entrant flow shops.
- Our study proves that the single-job problem is polynomial-time solvable regardless of whether the third operation is performed on Machine 1 or Machine 2 and develops optimal schedules with closed formulae for the optimal consistent and variable sublot sizes.
- Our study also proves that the multi-job problem is polynomial-time solvable when the third operation is performed on Machine 2 and develops optimal schedules with closed formulae for the optimal sublot sizes. However, the multi-job problem is *NP*-hard when the third operation is performed on Machine 1.
- A global lower bound on the makespan and a simple heuristic algorithm providing optimal or near-optimal schedules have been developed.

3. Single-job case

Our single-job problem in the two-machine re-entrant flow shop is explained as follows: A job-lot of U identical items has three operations to be performed. Each operation k $(k = 1,2,3)$ requires p_k time units of processing. There are two machines M_1 (Machine 1) and M_2 (Machine 2) operating independently. The first and second operations of the job-lot are performed on M_1 and M_2, respectively. A ***primary machine*** (M_1 or M_2) is re-visited by each item of the job lot for its third operation; hence the shop is a re-entrant flow shop. The job-lot is split into s sublots, and $x_{i,k}$ is the size of the i th sublot that completes its k th operation. Sublots of a job-lot can be immediately transferred from one machine to another for their next operation without waiting to complete other sublots. The goal is to determine the size and schedule of all sublots to minimize the makespan, which is the time to complete the third operation of the sublot processed as the last.

The assumptions made for the single-job problem are summarized here:

- The sublots of a job lot are processed without any interruption on every machine. i.e., pre-emption is not allowed.
- Each machine is ready at the beginning, say time zero, of the planning horizon. i.e., machines are not batching machines.
- At any time, only one item of a job lot can be processed by a machine.
- An unlimited storage space exists between the machines.
- An idle time on a machine may occur between processing sublots.

- Transfer times from one machine to another are negligibly so short and thus ignored.
- Setup times before processing the job-lot on a machine are negligibly so short and thus ignored.
- The number of sublots is known in advance and fixed from one machine to another.
- Processing times are known and deterministic.

3.1. Machine 2 is the primary machine

We first consider that M_2 is the primary machine where the third operation is performed. We investigate the problem for cases with consistent and variable sublots.

3.1.1. Consistent sublots

When the lot streaming is applied, sometimes there might be no advantage to change the size of the sublots after they have completed their processing on a machine. In this situation, it is reasonable to let the sublot sizes be constant (*consistent*) over all pairs of operations, i.e., $x_{i,k} = x_i$ for $i = 1, 2, \ldots, s$; $k = 1, 2, 3$ where $\sum_{1 \le i \le s} x_i = U$. ***Sublot availability*** assumption is used when sublots are consistent. i.e., a sublot can be processed at the next machine if all items in this sublot are completed on the current machine.

We start our analysis with the following lemma.

Lemma 1. *For the single-job problem where M_2 is the primary machine, it is sufficient to consider schedules of sublots where the last two operations of the sublots are processed consecutively on M_2.*

Proof. Consider any schedule of the consistent sublots. Suppose that there is a pair of sublots u and v, where the second operation of sublot v is immediately processed before the third operation of sublot u on M_2. Then interchanging the positions of sublots u and v on M_2 is feasible and does not increase makespan. On machine M_2, when all sublots, which are immediately processed before sublot u, are pair-wise interchanged with the second operation of sublot u, then it is possible to consecutively process the second and the third operations of sublot u on M_2. Similarly, it is possible to schedule consecutively the second and the third operations of all sublots on M_2.

From Lemma 1, the single-job problem can be illustrated by a network, as shown in Figure 1. Let $\overline{x} = (x_1, x_2, \ldots, x_s)$ denote the sublot sizes, and (k, i) be a node for the pair with operation k $(k = 1, 2, 3)$ and sublot i $(i = 1, \ldots, s)$ where $p_k x_i$ is the processing time of the k th operation of sublot i. The vertical arc from node $(1,\ i)$ to node $(2,\ i)$ indicates that sublot i cannot be processed on M_2 unless it is completed on M_1. The horizontal arc from node $(1,\ i)$ to node $(1,\ i+1)$ indicates that M_1 can start to process sublot $i+1$ upon the completion of sublot i on M_1. Similarly, the horizontal arc from $(2, i)$ to $(3, i)$ represents that the third operation of sublot i can be started when its second operation is completed on M_2.

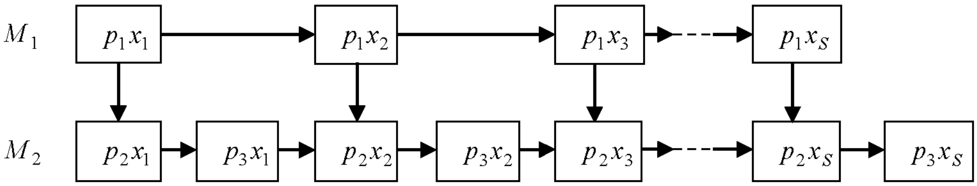

Figure 1. Network representation for the case where M_2 is the primary machine

Here, the goal is to determine the sublot sizes minimizing the ***critical path*** (longest path) length from node $(1, 1)$ to $(3, s)$, in which the sum of the processing times of the nodes on the critical path gives the length of the critical path.

The following theorem gives the optimal sublot sizes for the single-job problem where M_2 is the primary machine.

Theorem 1. *For the single-job problem where M_2 is the primary machine, the optimal consistent-sublot sizes are* $x_1 = U/(1+\alpha+\alpha^2+...+\alpha^{s-1})$, $x_i = \alpha^{i-1}x_1$ for $i = 2,...,s$ *where* $\alpha = (p_2+p_3)/p_1$, $U = \sum_{1\le i\le s} x_i$, *and the associated optimal makespan is* $C_{\max} = p_1x_1 + (p_2+p_3)\sum_{i=1}^{s} x_i = \left(p_1/(1+\alpha+\alpha^2+...+\alpha^{s-1}) + (p_2+p_3)\right)U$.

Proof. See the Appendix A. ■

Theorem 1 proves that the single-job problem where M_2 is the primary machine is equivalent to the single-job problem in the basic two-machine flow shop with processing times p_1 and p_2+p_3 on M_1 and M_2, respectively. From Theorem 1, it is clear that the optimal consistent-sublot sizes can be determined in $O(s)$ time.

Example 1. In this numerical example, we illustrate Theorem 1, in which the consistent sublots are optimal. Suppose that we have a job lot of 70 identical items that will be split into three sublots, and the processing times for its three operations are 2, 3, and 1 time-units, respectively. Then, from Theorem 1, we determine that the sublot sizes are found to be 10, 20, and 40 units for the first, second, and third sublots, respectively. That is, $x_1 = U/(1+\alpha+\alpha^2+...+\alpha^{s-1}) = 70/(1+2+2^{3-1}) = 10$, $x_2 = 2^1x_1 = (2)(10) = 20$, and $x_3 = 2^2x_1 = (4)(10) = 40$, where $\alpha = (p_2+p_3)/p_1 = (3+1)/2 = 2$. The optimal makespan is $C_{\max} = p_1x_1 + (p_2+p_3)\ U = (2)(10)+(3+1)(70) = 300$, as illustrated in Figure 2.

3.1.2. Variable sublots

In some cases, there might be some advantages to change the size of the sublots after they have completed their processing on a machine. Thus, variable sublots are preferred to the consistent sublots, using the ***item availability*** assumption where an individual item in a sublot can be processed at the next machine when this item is completed on the current machine.

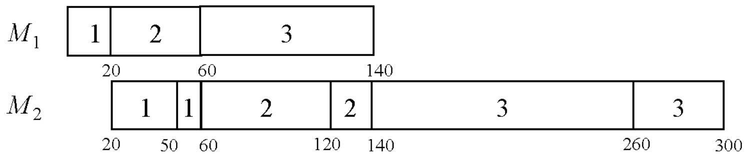

Figure 2. Optimal schedule of the sublots in Example 1

Remark 1. *There is no need to investigate the optimal solution for the single-job problem having variable sublots in the two-machine re-entrant flow shop where M_2 is the primary machine. The solution of the single-job problem having consistent sublots is also optimal for the single-job problem having variable sublots since only one set of sublot transfers from M_1 to M_2 is needed when the second and third operations are performed on M_2.*

3.2. Machine 1 is the primary machine

We now consider that M_1 is the primary machine where the third operation is performed. We again investigate the problem for cases with consistent and variable sublots.

3.2.1. Consistent sublots

Similar to the analysis given by Wang et al. (1997) for the basic two-machine re-entrant flow shop makespan minimization problem without lot streaming, we present the following lemma and theorem for finding the optimal solution to our problem having consistent sublots when M_1 is the primary machine. We first give the following definitions.

Definition 1. *A schedule is called a* ***compact schedule*** *if the first operations of all sublots are scheduled successively on M_1 and then followed by the third operations of all sublots.*

Definition 2. *A schedule is called a* ***permutation schedule*** *if all sublots are processed in the same order on both machines.*

Lemma 2. *For the single-job problem where M_1 is the primary machine, it is sufficient to consider only compact and permutation schedules of the sublots.*

Proof. Consider any feasible schedule σ with consistent sublots. We first show that σ can be transformed into a compact schedule on M_1 without worsening the makespan. Suppose we have a pair of two sublots, u and v, where the last (third) operation of sublot u immediately precedes the first operation of sublot v on M_1, i.e., $O_{u,3} \prec O_{v,1}$. Then interchanging their positions does not worsen the makespan.

When all sublots, which immediately follow sublot u, are pair-wise interchanged with sublot u, we assume that all first operations of the sublots are scheduled first on M_1. If any, we may eliminate the idle time between the first operations of any pair of successive sublots by moving the start time of the second sublot in the pair to the left. This movement does not affect the feasibility and does not change the makespan. Now, assume that an idle time exists between the last operations of any pair of successive sublots. Then we can eliminate it by moving all sublots except the last to the right. Again, this movement does not affect the feasibility and does not change the makespan. This shows that the first and the last operations of the job-lot are performed continuously without idle time between the sublots on M_1. Now, consider any optimal schedule σ, which is compact on M_1 but in which the processing order of the sublots on the first pair (M_1, M_2) of machines is different. Let sublots u and v be the first pair of sublots such that $O_{u,1} \underline{\pi} O_{v,2}$ and $O_{v,2} \underline{\mathrm{p}} O_{u,2}$. Let sublots u and v be the last pair of sublots such that $O_{u,1} \underline{\pi} O_{v,1}$ and $O_{v,2} \pi O_{u,2}$. Interchanging the order of $O_{u,2}$ and $O_{v,2}$ is possible and maintains compactness on M_1, and the makespan remains unchanged. This indicates that an optimal schedule, which is compact and the processing order of the sublots on the last pair (M_2, M_1) of machines is the same, exists.

Theorem 2. *Let $C_{\max}$ and $C'_{\max}$ denote the optimal makespan values of the single-job problem having consistent sublots in the two-machine re-entrant flow shop where M_1 is the primary machine and the single-job problem having consistent sublots in the basic three-machine flow shop, respectively. If $C'_{\max} > \sum_{i=1}^{s}(p_1 + p_3)x_i = (p_1 + p_3)U$ then $C_{\max} = C'_{\max}$; otherwise, $C_{\max} = (p_1 + p_3)U$.*

Proof. The single-job problem where M_1 is the primary machine can be represented by a network, as illustrated in Figure 3. Let $\bar{x} = (x_1, x_2, ..., x_s)$ denote the sublot sizes and (k, i) be a node for the pair with operation k $(k = 1,2,3)$ and sublot i $(i = 1, ..., s)$, having a weight of $p_k x_i$ that represents the sublot processing time. The vertical arc from node $(1, i)$ to node $(2, i)$ indicates that sublot i can be processed on M_2 upon its completion on M_1. The horizontal arc from node $(1, i)$ to node $(1, i+1)$ indicates that M_1 can start to process sublot $i+1$ upon the completion of sublot i on M_1. Similarly, the vertical arc from $(2, i)$ to $(3, i)$ represents that the third operation of a sublot can be started when the second operation is completed on M_2. In view of Lemma 2, we observe that the precedence constraint of arc between $(1, s)$ and $(3, 1)$ becomes redundant if $C'_{\max} > (p_1 + p_3)U$. Thus, an idle time on M_1 exists between the first operation of the last sublot and the third operation of the first sublot. However, if the arc between $(1, s)$ and $(3, 1)$ is removed from the network $N(\bar{x})$, the new network then represents the lot streaming problem in the three-machine flow shop. Therefore, it is clear that $C_{\max} = \max\{C'_{\max}, (p_1 + p_3)U\}$. It is obvious that $C_{\max} = C'_{\max}$ when $C'_{\max} > (p_1 + p_3)U$. Thus in this case, the lot streaming problems in the basic three-machine flow shop and the two-machine re-entrant flow shop are equivalent. However, $C_{\max} = (p_1 + p_3)U$ when $C'_{\max} \le (p_1 + p_3)U$. ■

As a result of Theorem 2, an optimal solution to the single-job problem where M_1 is the primary machine can be constructed by the optimal solution proposed by Glass et al. (1994) for the single-job problem having consistent sublots in the basic three-machine flow shop, as in the following corollary.

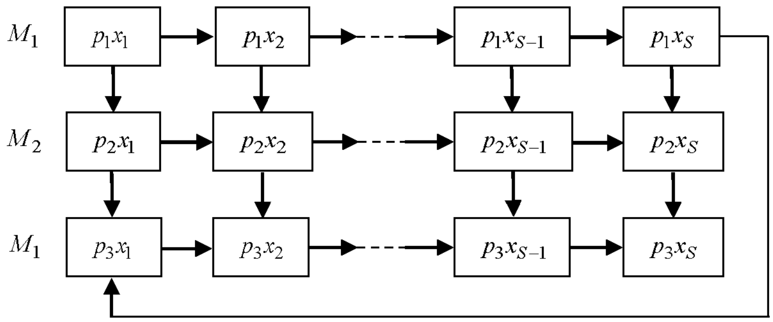

Figure 3. Network representation for the case where M_1 is the primary machine

Corollary 2. *When the makespan is minimized, the optimal consistent-sublot sizes for the single-job problem in the basic three-machine flow shop are also optimal for the single-job problem having consistent sublots in the two-machine re-entrant flow shop where M_1 is the primary machine, and they are as follows:*

(i) *If $p_2^2 \le p_1p_3$, then the optimal sublot sizes are:*

$$x_1 = \begin{cases} U(\beta-1)/(\beta^s-1) & \text{if } p_1 \ne p_3 \\ U/s & \text{if } p_1 = p_3 \end{cases}, \quad x_i = \beta^{i-1}x_1 \text{ for } 2 \le i \le s \text{ where}$$

$\beta = (p_2 + p_3)/(p_1 + p_2)$.

(ii) *If $p_2^2 > p_1p_3$, then there exists a crossover sublot h, which can be determined by a search algorithm in $O(\log s)$ time, for which the optimal sublot sizes are:*

$$x_h = \begin{cases} U/\{(\alpha^h-1)/(\alpha-1)+(\gamma^{s-h+1}-1)/(\gamma-1)-1\} & \text{if } p_1 \ne p_2, p_2 \ne p_3 \\ U/\{h-1+(\gamma^{s-h+1}-1)/(\gamma-1)\} & \text{if } p_1 = p_2, p_2 \ne p_3 \\ U/\{(\alpha^h-1)/(\alpha-1)+s-h\} & \text{if } p_1 \ne p_2, p_2 = p_3 \end{cases},$$

$x_i = \alpha^{h-i}x_h$ *for* $1 \le i \le h-1$, $x_i = \gamma^{i-h}x_h$ *for* $h \le i \le s$ *where* $\alpha = p_1/p_2$ *and* $\gamma = p_3/p_2$.

Example 2. Assume that we have a job lot of 70 identical items that will be split into three sublots, and the processing times for its three operations are 1, 4, and 2 time-units, respectively. This case corresponds to the second case in Corollary 2 since $p_2^2 = (4)^2 = 16 > p_1p_3 = (1)(2) = 2$. The size of the crossover sublot h is determined by $x_h = U/\{(\alpha^h - 1)/(\alpha - 1) + (\gamma^{s-h+1} - 1)/(\gamma - 1) - 1\}$ where $\alpha = p_1 / p_2 = 1/4$ and $\gamma = p_3 / p_2 = 1/2$ since $p_1 = 1 \neq p_2 = 4 \neq p_3 = 2$.

When $h = 1$, $x_1 = U/\left(\frac{\alpha^h - 1}{\alpha - 1} + \frac{\gamma^{s-h+1} - 1}{\gamma - 1} - 1\right) = 70/\left(\frac{(1/4)^1 - 1}{(1/4) - 1} + \frac{(1/2)^{3-1+1} - 1}{(1/2) - 1} - 1\right) =$

$\frac{70}{1.75} = 40$, $x_2 = \gamma^{2-1} x_1 = (1/2)^1 (40) = 20$, $x_3 = \gamma^{3-1} x_1 = (1/2)^2 (40) = 10$, and $C'_{\max} = 340$.

When $h = 2$, $x_2 = U/\left(\frac{\alpha^h - 1}{\alpha - 1} + \frac{\gamma^{s-h+1} - 1}{\gamma - 1} - 1\right) = 70/\left(\frac{(1/4)^2 - 1}{(1/4) - 1} + \frac{(1/2)^{3-2+1} - 1}{(1/2) - 1} - 1\right) =$

$\frac{70}{1.75} = 40$, $x_1 = \alpha^{2-1} x_1 = (1/4)^1 (40) = 10$, $x_3 = \gamma^{3-2} x_1 = (1/2)^1 (40) = 20$, and $C'_{\max} = 330$ (See Figure 4a).

When $h = 3$, $x_3 = U/\left(\frac{\alpha^h - 1}{\alpha - 1} + \frac{\gamma^{s-h+1} - 1}{\gamma - 1} - 1\right) = 70/\left(\frac{(1/4)^3 - 1}{(1/4) - 1} + \frac{(1/2)^{3-3+1} - 1}{(1/2) - 1} - 1\right) \cong$

53.33, $x_1 = \alpha^{3-1} x_1 = (1/4)^2 (53.33) = 3.33$, $x_2 = \alpha^{3-2} x_1 = (1/4)^1 (53.33) = 13.33$, and $C'_{\max} = 390$.

It is clear that the optimal sublots are achieved when $h = 2$, and their sizes are $x_1 = 10$, $x_1 = 40$, and $x_3 = 20$. Note that the optimal makespan is $C_{\max} = C'_{\max} = 330$ since $C'_{\max} = 330 > (p_1 + p_3)U = (1+2)(70) = 210$, and the optimal schedule is obtained by carrying the third operations of the sublots in the three-machine flow shop problem to M_1, as illustrated in Figure 4b.

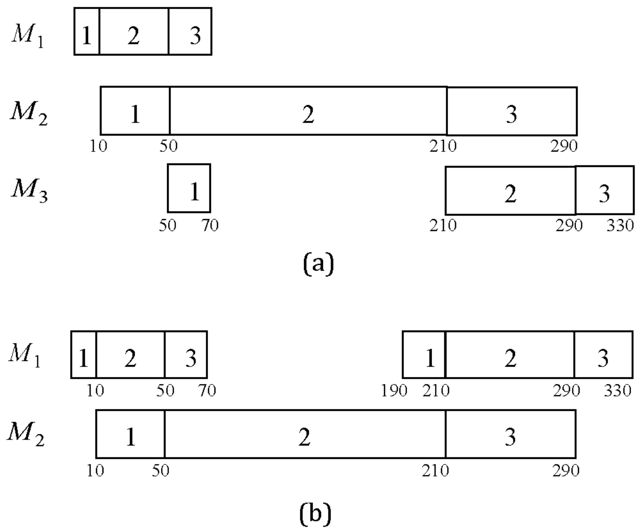

Figure 4. Optimal schedules with consistent sublots for the single-job problem in Example 2: (a) Three-machine flow shop; (b) Two-machine re-entrant flow shop.

3.2.2. Variable sublots

As a result of Theorem 2, an optimal solution to the single-job problem having variable sublots where M_1 is the primary machine can be constructed by the optimal solution proposed by Trietsch & Baker (1993) for the single-job problem with variable sublots in the basic three-machine flow shop, as in the following corollary.

Corollary 3. *When the makespan is minimized, the optimal variable-sublot sizes in the single-job problem in the basic three-machine flow shop are also optimal for the single-job problem having the variable sublots in the two-machine re-entrant flow shop where M_1 is the primary machine, and they are as follows:*

(i) *If $p_2^2 \le p_1 p_3$, then the consistent sublots are optimal, and they are:* $x_1 = U(\beta - 1)/(\beta^s - 1)$, $x_i = \beta^{i-1} x_1$ *for* $2 \le i \le s$ *where* $\beta = (p_2 + p_3)/(p_1 + p_2)$.

(ii) *If $p_2^2 > p_1 p_3$, then the variable sublots are optimal,*

- *the optimal sublot sizes between* M_1 and M_2 *are:* $x_1 = U(\alpha - 1)/(\alpha^s - 1)$, $x_i = \alpha^{i-1} x_1$ *for* $2 \le i \le s$ *where* $\alpha = p_2 / p_1$, *and*
- *the optimal sublot sizes between* M_2 and M_1 *are:* $x_1 = U(\gamma - 1)/(\gamma^s - 1)$, $x_i = \gamma^{i-1} x_1$ *for* $2 \le i \le s$ *where* $\gamma = p_3 / p_2$.

From Corollary 3, it is clear that the optimal variable-sublot sizes can be determined in $O(s)$ time.

Example 3. In this numerical example, we illustrate the second case of Corollary 3, in which the variable sublots are optimal since $p_2^2 > p_1 p_3$. Assume that we have a job lot of 15 identical items that will be split into two sublots, and the processing times for its three operations are 1, 2, and 1 time-units, respectively. From Corollary 2, the sublot sizes between M_1 and M_2 are found to be $x_1 = 15(2-1)/(2^2 - 1) = 5$ and $x_2 = (2^1)(5) = 10$ where $\alpha = p_2 / p_1 = 2/1 = 2$ and $p_2^2 = (2)^2 = 4 > p_1 p_3 = (1)(1)$. (See Figure 5a). Similarly, the sublot sizes between M_2 and M_1 are calculated as $x_1 = 15((1/2) - 1)/((1/2)^2 - 1) = 10$ and $x_2 = ((1/2)^1)(10) = 5$ since $\gamma = p_3 / p_2 = 1/2$. Thus, the optimal makespan of the problem having variable sublots in the basic three-machine flow shop is 40, and the optimal schedule of the problem in the two-machine re-entrant flow shop is obtained by carrying the third operations of the sublots in the optimal schedule of the problem in the three-machine flow shop to M_1, as illustrated in Figure 5b.

4. Multi-job case

In this section, we extend our problem presented to the multi-job case. The multi-job problem is explained as follows: There is a job-lot set $J = \{j | j = 1, 2, \ldots, n\}$ where each job-lot has U_j identical items of type j. Let $p_{j,k}$ be the processing time for

k th $(k = 1,2,3)$ operation of job-lot j. There are two machines M_1 and M_2. Each job-lot is processed first on M_1, on M_2 for its second operation before returning to the primary machine (M_1 or M_2) for the third operation. Suppose that job-lot j is split into s_j sublots, then our goal is to determine the sublot sizes for each job-lot and the schedule of all sublots and job lots to minimize the makespan.

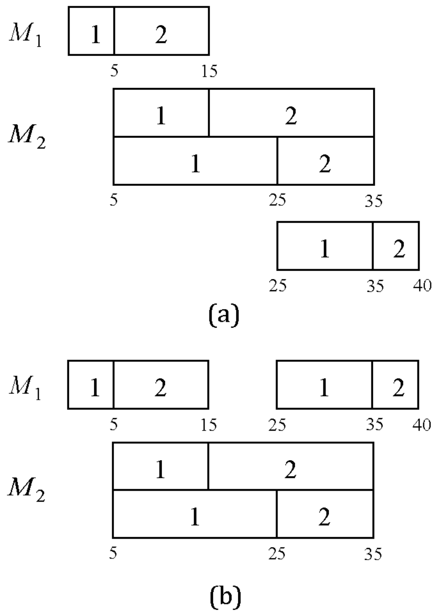

Figure 5. Optimal schedules with variable sublots for the single-job problem in Example 3: (a) Three-machine flow shop; (b) Two-machine re-entrant flow shop.

For the multi-job problem, we consider all assumptions made for the single-job problem. Furthermore, we do not allow the ***intermingling*** of different job lots. That is, once a sublot of a job-lot is started on a machine, all other job lots should wait until all of the remaining sublots of that job-lot are completed on the same machine. Note that intermingling the sublots belonging to different job lots may further reduce the makespan, but we focus on the no-intermingling case in our study. Intermingling can be considered in a future study as future research, as we point out in Section 5.

As in the case of the single-job problem, we investigate two cases associated with the primary machine.

4.1. Machine 2 is the primary machine

The following lemma gives the basic structure of the job-sequence for the multi-job problem where M_2 is the primary machine.

Lemma 3. *For an optimal solution of the multi-job problem where M_2 is the primary machine, it is sufficient to consider the job-sequence in which the last two operations of each sublot belonging to a job-lot are processed successively on M_2.*

Proof. Omitted since it is similar to the proof of Lemma 1. ■

The multi-job problem where M_2 is the primary machine can be decomposed into two sub-problems: (a) the ***job-sequencing*** and (b) the ***sublot-sizing***.

4.1.1. Job-sequencing sub-problem

The multi-job problem reduces to the determination of the optimal sequence of job lots when the sublot-sizing sub-problem for each job-lot has already been solved. That is, the job-sequencing sub-problem needs to be solved. Suppose that each job-lot j is independently split into sublots by Corollary 2 or Corollary 3. Let

RI_j = time lag between the start of the first operation on M_1 and the latest start time of the second operation on M_2 for job-lot j. i.e., the latest delay time, simply called run-in-delay for job-lot j on M_2 without affecting the completion time of job-lot j (called as ***run-in delay for Operation 2***).

RO_j = time lag between the completion times of the first and the second operations for job-lot j (called as ***run-out delay for Operation 2***).

RI'_j = time lag between the latest start of the second operation on M_2 and the latest start time of the third operation on M_1 for job-lot j. i.e., the latest delay time, simply called run-in-delay for job-lot j on M_1 without affecting the completion time of job-lot j (called as ***run-in delay for Operation 3***).

RO'_j = time lag between the completion times of the second and the third operations for job-lot j (called as ***run-out delay for Operation 3***).

The following theorem provides the optimal solution to the job-sequencing sub-problem.

Theorem 3. *Given the solution of the sublot-sizing sub-problem, job-lot v precedes job-lot z in an optimal job-sequence if* $\min\{RI_v, RO_z\} \le \min\{RI_z, RO_v\}$, *where* $RI_j = \min_{1\le i\le s_j}\left\{\sum_{r=1}^{i} p_{j,1}x_{j,r} - \sum_{r=1}^{i-1}(p_{j,2}+p_{j,3})x_{j,r}\right\}$, *and* $RO_j = RI_j + (p_{j,2}+p_{j,3}-p_{j,1})U_j$ *for any job-lot j.*

Proof. See the Appendix B. ■

4.1.2. Sublot-sizing sub-problem

The sublot-sizing sub-problem needs to be solved for each job-lot when the job-sequencing sub-problem has already been solved. The following theorem provides the optimal solution to the sublot-sizing sub-problem.

Theorem 4. *Given the solution of the job-sequencing sub-problem, the optimal sublot sizes in a job-lot processed in position* $[j]$ *of the job-sequence are* $x_{[j],1} = U_{[j]}/(1+\alpha+\alpha^2 \quad +\ldots+\alpha^{s[j]-1})$, $x_{[j],i} = \alpha^{i-1}x_{[j],1}$ *for* $i = 2,\ldots,s_{[j]}$ *where* $\alpha = (p_{[j],2} + p_{[j],3})/p_{[j],1}$.

Proof. See the Appendix C. ■

From Theorems 3 and 4, we have the following result.

Corollary 4. *Solving the sublot-sizing sub-problem using Theorem 4 and then solving the job-sequencing sub-problem using Theorem 3 provides the optimal solution to the multi-job problem where* M_2 *is the primary machine.*

Based on Corollary 4, we propose the following exact-solution algorithm with a computational complexity of $O(n\log n)$ to solve the multi-job problem where M_2 is the primary machine and n is the total number of job lots.

Algorithm 1.

Step 1: [*Sublot-sizing*] Calculate the size for each sublot of the job-lot in the set $J = \{j|j = 1,2,\ldots,n\}$ as $x_{j,1} = U_j/(1+\alpha+\alpha^2+\ldots+\alpha^{s_j-1})$ and $x_{j,i} = \alpha^{i-1}x_{j,1}$ for $i = 2,\ldots,s_j$ where $\alpha = (p_{j,2} + p_{j,3})/p_{j,1}$.

Step 2: [*Job-sequencing*]

(a) Set $RI_j = p_{j,1}U_j/(1+\alpha+\alpha^2+\ldots+\alpha^{s_j-1})$ and $RO_j = RI_j + (p_{j,2} + p_{j,3} - p_{j,1})U_j$.

(b) To obtain the job-sequence $\pi = \{\pi[j] \| j = 1,2,\ldots,n\}$, consider all jobs in the job-lot set J and apply Johnson's Algorithm with processing times on M_1 and M_2 replaced by RI_j and RO_j, respectively.

(ii) Calculate the associated makespan as

$$C_{\max} = \max_{1\le w\le n}\left(\sum_{j=1}^{w} RI_{\pi[j]} - \sum_{j=1}^{w-1} RO_{\pi[j]}\right) + \sum_{j=1}^{n}(p_{\pi[j],2} + p_{\pi[j],3})U_{\pi[j]}$$

4.2. Machine 1 is the primary machine

This section considers the multi-job problem where M_1 is the primary machine. Unfortunately, this problem is more complicated than the multi-job problem where M_2 is the primary machine discussed in Section 4.1.

Theorem 5. *The multi-job problem where* M_1 *is the primary machine is NP-hard in the strong sense.*

Proof. Suppose that each job-lot has one sublot only. This special case of our multi-job problem is equivalent to the multi-job problem without lot streaming in the basic two-machine re-entrant flow shop where M_1 is the primary machine. It has been proven by Wang et al. (1997) that this special case is *NP*-hard in the strong sense. Thus, our multi-job problem where M_1 is the primary machine is also strongly *NP*-hard. ■

The following lemma restricts our search to the compact and permutation schedules of the job lots for the optimal schedule of the multi-job problem where M_1 is the primary machine.

Lemma 4. *For an optimal solution of the multi-job problem where M_1 is the primary machine, it is sufficient to consider only compact and permutation schedules of the job lots.*

Proof. Omitted since it is similar to the proof of Lemma 2. ■

4.2.1. A Polynomial-time solvable case

Since the multi-job problem where M_1 is the primary machine has been shown to be *NP*-hard in Theorem 5, an optimal algorithm solving the problem in polynomial-time is impossible. Therefore, we first examine a polynomial-time solvable case of the problem that corresponds to the case, in which the sublots of all job lots are independently determined by Corollaries 2 or 3 and the idle time between the first and the third operations of all jobs on M_1 is zero.

Let I_j be the idle time on M_1 between the first and the third operations of job-lot j when it is independently split into sublots by Corollaries 2 or 3. The following theorem provides the optimal schedule for this special case.

Theorem 6. *If $I_j = 0$ for every job-lot j, then arbitrarily sequencing all jobs as illustrated in Figure 6 is an optimal schedule for the multi-job problem where M_1 is the primary machine.*

Proof. If $I_j = 0$ for every job-lot j, there will be no idle time between the first and the third operations of job-lot j on M_1 when job lots are arbitrarily sequenced. Then, the time to complete all operations of job-lot j becomes $T_j = (p_{j,1} + p_{j,3})U_j$ $+I_j = (p_{j,1} + p_{j,3})U_j$ when it is independently split into sublots, and $C_{\max} = \sum_{j=1}^{n} T_j =$ $\sum_{j=1}^{n}(p_{j,1} + p_{j,3})U_j$ becomes the optimal makespan.

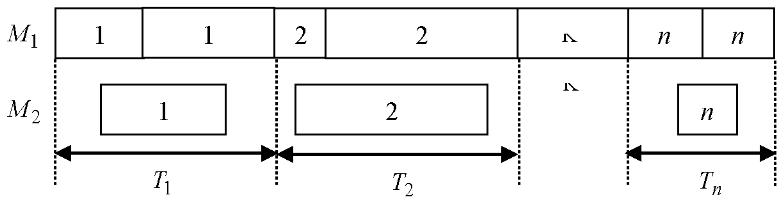

Figure 6. Optimal schedule obtained by Theorem 6

4.2.2. Proposed heuristic algorithm

For a given job-sequence π, we define the job-lot $\pi[d]$ such that $C_{\pi[d-1],2} \le \sum_{j=1}^{n} p_{j,1}U_j < C_{\pi[d],2}$ where $C_{\pi[d],2}$ is the time to complete the second operation of job-lot $\pi[d]$, and $C_{\pi[d],2} = C_2(\pi) - \sum_{j=d+1}^{n} p_{\pi[j],2}U_{\pi[d]} = \max_{j=1,..,n}\left(\sum_{i=1}^{j} RI_{\pi[i]} - \sum_{i=1}^{j-1} RO_{\pi[i]}\right) + \sum_{j=1}^{n} p_{\pi[j],2}U_{\pi(j)}$ where $C_2(\pi)$ is the completion time of all job lots in sequence π on M_2, and $C_{\pi[d-1],2} = C_{\pi[d],2} - p_{\pi[d],2}U_{\pi[d]}$. Here job-lot $\pi[d]$ that will be used to develop the proposed algorithm is called a ***partition job-lot*** and is the first job whose second operation finishes later than the completion of all first operations on M_1 (see Figure 7). From the definition of the job-lot $\pi[d]$, it is clear that no idle time exists between job lots following job-lot $\pi[d]$ on M_2. Thus, permutation sequence π is partitioned into three subsequences: $J_B = \{\pi[j] \mid j = 1,\ldots,\ d-1\}$, $J_D = \{\pi[j] \mid j = d\}$, and $J_A = \{\pi[j] \mid j = d+1,,\ldots,n\}$.

We propose the following heuristic algorithm with a computational complexity of $O(n\log n)$ to solve the multi-job problem where M_1 is the primary machine.

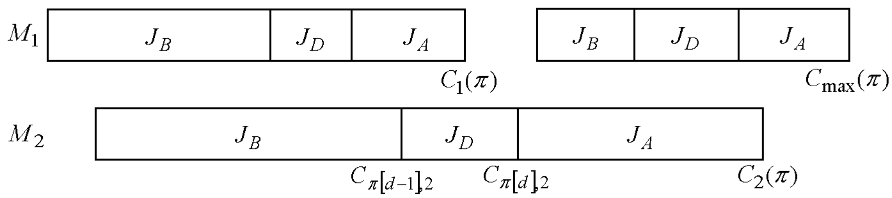

Figure 7. Partition job-lot in position d of the job-sequence π

Algorithm 2.

Step 1: For each job lot j,

(a) If sublots are considered as consistent, then use the sublot sizes in Corollary 2; otherwise (variable sublots), use the sublot sizes in Corollary 3.

(b) Compute the makespan T_j, and idle time on M_1 as $I_j = T_j - (p_{j,1} + p_{j,3})U_j$.

Step 2: Divide the job-lot set J into two sets: $J^1 = \{j \mid I_j = 0\}$ and $J^2 = \{j \mid I_j > 0\}$.

Step 3: If $J^2 = \varnothing$, then any arbitrary sequence of job lots is optimal, and the optimal makespan is $C^*_{\max} = \sum_{j=1}^{n}(p_{j,1} + p_{j,3})U_j$, stop; otherwise, go to Step 4.

Step 4: Compute the run-in delays (RI_j and RI'_j) and run-out delays (RO_j and RO'_j). Schedule all job lots $J = \{j \mid j = 1,\ldots,n\}$ by applying Johnson's Algorithm with processing times on M_1 and M_2 replaced by RI_j and RO_j to obtain the job-sequence $\pi = \{\pi[j] \mid j = 1,\ldots,n\}$.

Step 5: In the job-sequence π, determine the partition job-lot $\pi[d]$ such that $C_{\pi[d-1],2} \le \sum_{j=1}^{n} p_{j,1}\, U_j < C_{\pi[d],2}$ where $C_{\pi[d],2} = \max_{j=1,\ldots,n}\left(\sum_{i=1}^{j} RI_{\pi[i]} - \sum_{i=1}^{j-1} RO_{\pi[i]}\right) + \sum_{j=1}^{d} p_{\pi[j],2} U_{\pi(j)}$, and $C_{\pi[d-1],2} = C_{\pi[d],2} - p_{\pi[d],2}\, U_{\pi[d]}$.

Step 6: Compute the associated makespan $C_{\max}(\pi)$ as:

$$C_{\max}(\pi) = \max\Big\{\sum_{j=1}^{n} p_{\pi[j],1} U_{\pi[j]} + \sum_{j=1}^{d-1} p_{\pi[j],3} U_{\pi[j]},\ \max_{j=1,\ldots,n}\Big\{\sum_{i=1}^{j} RI_{\pi[i]} - \sum_{i=1}^{j-1} RO_{\pi[i]}\Big\} + \sum_{j=1}^{d-1} p_{\pi[j],2} U_{\pi[j]} + \max_{j=d,\ldots,n}\Big\{\sum_{i=d}^{j} RI'_{\pi[i]} - \sum_{i=d}^{j-1} RO'_{\pi[i]}\Big\}\Big\} + \sum_{j=d}^{n} p_{\pi[j],3} U_{\pi[j]}$$

Step 7: If $C_{\max}(\pi) = \sum_{j=1}^{n} (p_{j,1} + p_{j,3}) U_j$, then the job-sequence π is optimal, stop; otherwise, go to Step 8.

Step 8: Consider the job lots in $J_D \cup J_A = \{\pi[j] \mid j = d,\ldots,n\}$, and apply Johnson's Algorithm with processing times on M_1 and M_2 replaced by RI'_j and RO'_j to obtain the partial job-sequence $\sigma = \{\sigma[j] \mid j = 1,\ldots,n-d+1\}$.

Step 9: Set the final sequence of job lots as $\varphi = \{\pi, \sigma\}$ where $\pi = \{\pi[j] \mid j = 1,\ldots,d-1\}$ followed by $\sigma = \{\sigma[j] \mid j = 1,\ldots,n-d+1\}$. The associated makespan is

$$C_{\max}(\phi) = \max\Big\{\sum_{j=1}^{n} p_{\pi[j],1} U_{\pi[j]} + \sum_{j=1}^{d-1} p_{\pi[j],3} U_{\pi[j]},\ \max_{j=1,\ldots,n}\Big\{\sum_{i=1}^{j} RI_{\pi[i]} - \sum_{i=1}^{j-1} RO_{\pi[i]}\Big\} + \sum_{j=1}^{d-1} p_{\pi[j],2} U_{\pi[j]} + \max_{j=d,\ldots,n}\Big\{\sum_{i=d}^{j} RI'_{\sigma[i]} - \sum_{i=d}^{j-1} RO'_{\sigma[i]}\Big\} + \sum_{j=d}^{n} p_{\sigma[j],3} U_{\sigma[j]}$$

4.2.2. Lower bounds on the makespan

We now develop four lower bounds on the makespan, and then we take the maximum of these lower bounds as a global lower bound, which will be used to test Algorithm 2.

Lower bound 1. This lower bound is obtained by assuming that there will be no idle time between the first and the third operations of each job lot on M_1. Thus, the natural lower bound is

$$LB_1 = \sum_{j=1}^{n} (p_{j,1} + p_{j,3}) U_j \ , \qquad (1)$$

which is equivalent to the total processing time of all job lots on M_1.

Lower bound 2. We derive the second lower bound as

$$LB_2 = \min_{j=1,..,n} \left(RI_j \right) + \sum_{j=1}^{n} p_{j,2} U_j + \min_{j=1,..,n} \left(RO'_j \right) \qquad (2)$$

by assuming that the job lot with the minimum run-in delay for Operation 2 is processed as the first job-lot in the job-sequence, M_2 operates continuously without any idle time between job lots, and the job lot with the minimum run-out delay for Operation 3 is processed as the last job lot in the job-sequence.

Lower bound 3. To derive our third lower bound, we assume that all job lots do not wait for their operations to be performed on M_2. For a sequence π, we can establish the third lower bound as

$$LB_3 = \max_{j=1,..,n} \left(\sum_{i=1}^{j} RI_{\pi[i]} + \sum_{i=1}^{j-1} \Delta_{\pi[i]}^{1,2} + \sum_{i=j}^{n} p_{\pi[i],2} \, U_{\pi(i)} \right) + \min_{j=1,..,n} \left(RO'_j \right) \qquad (3)$$

where $\pi[i]$ is the job-lot in position i of the job-sequence π, and $\Delta_{\pi[i]}^{1,2}$ is the overlapping time for job lot $\pi[i]$ when both M_1 and M_2 are busy (i.e., operating continuously without idle time between sublots), as illustrated in Figure 8.

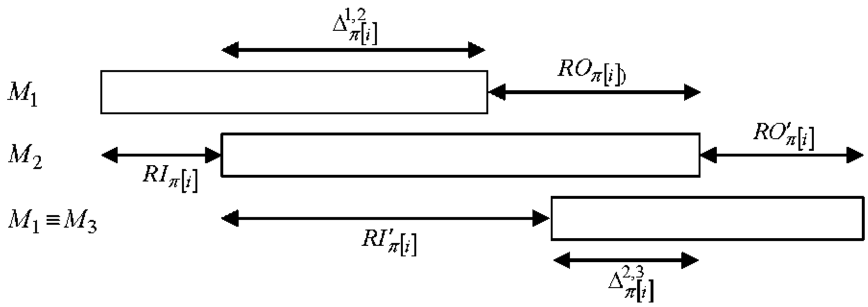

Figure 8. Run-in and run-out delays

We can rewrite (3) as

$$\begin{aligned} LB_3 &= \max_{j=1,..,n} \left\{ \sum_{i=1}^{j} RI_{\pi[i]} + \sum_{i=1}^{j-1} (p_{\pi[i],2} U_{\pi[i]} - RO_{\pi[i]}) + \sum_{i=j}^{n} p_{\pi[i],2} U_{\pi[i]} \right\} + \min_{j=1,..,n} \left\{ RO'_j \right\} \\ &= \max_{j=1,..,n} \left\{ \sum_{i=1}^{j} RI_{\pi[i]} + \sum_{i=1}^{j-1} p_{\pi[i],2} U_{\pi[i]} - \sum_{i=1}^{j-1} RO_{\pi[i]} + \sum_{i=j}^{n} p_{\pi[i],2} U_{\pi[i]} \right\} + \min_{j=1,..,n} \left\{ RO'_j \right\} \\ &= \max_{j=1,..,n} \left\{ \sum_{i=1}^{j} RI_{\pi[i]} - \sum_{i=1}^{j-1} RO_{\pi[i]} \right\} + \sum_{j=1}^{n} p_{[i],2} U_{[i]} + \min_{j=1,..,n} \left\{ RO'_j \right\} \qquad (4) \end{aligned}$$

Note that the last two terms in (4) are constant and independent from the sequence, and the first term, $\max_{j=1,..,n} \left(\sum_{i=1}^{j} RI_{\pi[i]} - \sum_{i=1}^{j-1} RO_{\pi[i]} \right)$, gives the total idle time on M_2 before completing the second operations of all job lots. The first term equals Johnson's expression in which the processing times on M_1 and M_2 are replaced by the run-in and run-out delays, respectively. Thus, the job-sequence π is obtained by job-lot k preceding job-lot l if $\min\{RI_k, RO_l\} \le \min\{RO_k, RI_l\}$.

Therefore, we obtain the third lower bound as

$$LB_3 = C^*_{\max}(JA(RI, RO)) + \min_{j=1,..,n}\{RO'_j\} \tag{5}$$

where $C^*_{\max}(JA(RI, RO))$ is the makespan obtained by Johnson's Algorithm (*JA*) with processing times on M_1 and M_2 replaced by RI_j and RO_j, respectively.

Lower bound 4. For any job-sequence π, we can establish the fourth lower bound as

$$LB_4 = \min_{j=1,..,n}\{RI_j\} + \max_{j=1,..,n}\left\{\sum_{i=1}^{j} RI'_{\pi[i]} + \sum_{i=1}^{j-1} \Delta^{2,3}_{\pi[i]} + \sum_{i=j}^{n} p_{\pi[i],3} U_{\pi[i]}\right\} \tag{6}$$

where $\Delta^{2,3}_{\pi[i]}$ is the overlapping time of the second and third operations for job lot $\pi(i)$ as shown in Figure 8.

Equation (6) can be rewritten as

$$\begin{aligned} LB_4 &= \min_{j=1,..,n}\{RI_j\} + \max_{j=1,..,n}\left\{\sum_{i=1}^{j} RI'_{\pi[i]} + \sum_{i=1}^{j-1} (p_{\pi[i],3} U_{\pi[i]} - RO'_{\pi[i]}) + \sum_{i=j}^{n} p_{\pi[i],3} U_{\pi[i]}\right\} \\ &= \min_{j=1,..,n}\{RI_j\} + \max_{j=1,..,n}\left\{\sum_{i=1}^{j} RI'_{\pi[i]} - \sum_{i=1}^{j-1} RO'_{\pi[i]}\right\} + \sum_{i=1}^{n} p_{\pi[i],3} U_{\pi[i]} \end{aligned} \tag{7}$$

Note that the second term in (7), $\max_{j=1,..,n}\left\{\sum_{i=1}^{j} RI'_{\pi[i]} - \sum_{i=1}^{j-1} RO'_{\pi[i]}\right\}$, is minimized by job-lot k preceding job lot l in the job-sequence if $\min\{RI'_k, RO'_l\} \le \min\{RO'_k, RI'_l\}$. Therefore, we obtain the fourth lower bound as

$$LB_4 = \min_{j=1,..,n}\{RI_j\} + C^*_{\max}(JA(RI', RO')) \tag{8}$$

where $C^*_{\max}(JA(RI', RO'))$ is the makespan obtained by Johnson's Algorithm with processing times on M_1 and M_2 replaced by RI'_j and RO'_j, respectively.

The global lower bound GLB becomes the maximum of the lower bounds developed above. i.e., $GLB = \max_{i=1,...,4}\{LB_i\}$.

Example 4. As an illustration of the proposed algorithm and the global lower bound, we consider the five-job problem in Table 1.

Table 1. Processing times, number of sublots, and lot sizes

j	$p_{j,1}$	$p_{j,2}$	$p_{j,3}$	s_j	U_j
1	3	2	3	4	40
2	1	2	2	3	30
3	1	2	7	2	20
4	1	4	2	3	70
5	2	2	1	3	35

When all job lots are independently split into their number of consistent sublots, the sublot sizes and T_j and I_j values are obtained, as illustrated in Table 2.

Table 2. Sublot sizes with T_j and I_j values

j	$x_{j,1}$	$x_{j,2}$	$x_{j,3}$	$x_{j,4}$	T_j	I_j
1	10	10	10	10	240	0
2	6	12	12	-	90	0
3	5	15	-	-	160	0
4	10	40	20	-	330	120
5	14	14	7	-	105	0

Job-lot set J is decomposed into two job-lot sets, $J^1 = \{1, 2, 3, 5\}$ and $J^2 = \{4\}$. We continue with Step 4 of Algorithm 2 since the job-lot set J^2 is not empty. The run-in and run-out delays for each job lot are obtained as shown in Table 3.

Table 3. Run-in and run-out delays

j	RI_j	RO_j	RI'_j	RO'_j
1	30	20	20	30
2	6	24	12	24
3	5	105	10	105
4	10	220	180	40
5	28	28	42	7

The application of Johnson's Algorithm with processing times on M_1 and M_2 replaced by RI_j and RO_j; respectively, gives the job-sequence $\pi = \{3, 2, 4, 5, 1\}$. The partition job-lot is job 2, and it is in the second position (i.e., $d = 2$) of the sequence π. The associated makespan $C_{\max}(\pi)$ for the sequence π is computed as 805. The global lower bound becomes $GLB = \max\{LB_1, LB_2, LB_3, LB_4\} = 805$ where

$$LB_1 = \sum_{j=1}^{n} (p_{j,1} + p_{j,3})U_j = (3+3)(40) + (1+7)(20) + (1+2)(70) + (2+1)(35) = 805 ,$$

$$LB_2 = \min_{j=1,..,n}\left(RI_j\right) + \sum_{j=1}^{n} p_{j,2}U_j + \min_{j=1,..,n}\left(RO'_j\right) = \min\{30, 6, 5, 10, 28\} + ((2)(40) + (2)(30)$$

$$+(4)(70) + (2)(35) + \min\{30, 24, 105, 40, 7\} = 542 ,$$

$$LB_3 = C^*_{\max}\left(JA\left(RI, RO\right)\right) + \min_{j=1,..,n}\left(RO'_j\right) = C^*_{\max}\left(4-2-3-1-5\right) + \min\{30, 24, 105, 40, 7\}$$

$= 535 + 7 = 542$,

$LB_4 = \min_{j=1,..,n} \{RI_j\} + C^*_{\max}(JA(RI', RO')) = \min\{30, 6, 5, 10, 28\} + C^*_{\max}(3-1-4-2-5)$

$= 5 + 560 = 565$.

The job-sequence $\pi = \{3, 2, 4, 5, 1\}$ is optimal since the associated makespan equals the natural lower bound LB_1. Thus, we stop.

4.2.3. Computational experiments and results

The efficiency measure of Algorithm 2 is the computational time required to solve the problem. However, its computational time is not measured provided since it is relatively very short, less than a few seconds. On the other hand, to test the effectiveness of Algorithm 2, we generate the parameters for our problem instances as follows:

n: number of job lots, $n \in \{5, 10, 15, 20, 25, 50, 75, 100\}$.

$p_{j,k}$: k th operation's processing time for job lot j is randomly generated form from a discrete uniform distribution over [1, 10], including the lower and upper limits.

s_j : number of sublots for any job lot j is randomly generated form from a discrete uniform distribution over [2, 10].

U_j: lot size for any job lot j is randomly generated form from a discrete uniform distribution over [2, 50].

For each possible number of job lots from 5 to 100, we first generate 100 problem instances in which the. The processing times for all operations are randomly distributed without any dominance of a specific operation, and a total of 800 problem instances are tested. The following statistics are collected:

NT_Z = number of times percent deviation is zero (i.e., the heuristic makespan equals the global lower bound).

$NT_{(0,1]}$ = number of times the percent deviation is greater than zero but less than or equal to 1 (i.e., $C^H_{\max} \le 1.01 GLB$).

AVE = average percent deviation.

MAX = maximum percent deviation.

From the results of our experiments, we observed that Algorithm 2 finds the optimum makespan (i.e., the heuristic makespan equals the global lower bound) for all 800 test problems when all processing times are randomly generated without any dominance of a specific operation. That is, $NT_Z = 800$.

However, to evaluate the effectiveness of Algorithm 2 when the same operation for all job lots is dominant, we repeated our computational experiments with three data sets. The first data set, D1, assumes that the maximum processing time is on the first operation for all job lots, i.e., $p_{j,1} \ge \max\{p_{j,2}, p_{j,3}\}$ for $\forall j$. Similarly, the second and third data sets D2 and D3 correspond to the cases where $p_{j,2} \geq \max\{p_{j,1}, p_{j,3}\}$ and $p_{j,3} \geq \max\{p_{j,1}, p_{j,2}\}$ for $\forall j$, respectively.

In each of the data sets, we assume that the processing time of the dominant operation for each job-lot is randomly generated form from a discrete uniform distribution over [6, 10], and the processing times of the other operations are randomly generated form from a discrete uniform distribution over [1, 5]. Our experiments with data sets D2 and D3 show that the global lower bound equals the heuristic makespan in all 800 problem instances tested when either the first or third operation is dominant. This result means that the global lower bound is effective when the first or third operation is dominant. However, the same argument is not valid for the case, where the second operation is dominant, since the global lower bound equals the heuristic makespan in 336 problem instances out of 800, as illustrated in Table 4.

From Table 4, it is clear that the heuristic makespan deviates 1 percent from the global lower bound in 790 problem instances out of 800 for the case where the second operation is dominant. In the remaining ten problem instances when $n = 5$, the average and maximum deviations from the global lower bound are 0.352 percent and 2.055 percent, respectively. It should also be noticed that the average and maximum deviations decrease as the number of jobs increases.

Table 4. Performance of Algorithm 2 when the second operation is dominant

n	$NPIS$	NT_Z	$NT_{(0,1]}$	AVE	MAX
5	100	45	45	0.352	2.055
10	100	30	70	0.136	0.656
15	100	40	60	0.076	0.569
20	100	37	63	0.050	0.231
25	100	36	64	0.036	0.116
50	100	37	63	0.014	0.044
75	100	58	42	0.006	0.026
100	100	53	47	0.005	0.021

Given the results of our computational experiments, we conclude that Algorithm 2 is quite effective in solving the multi-job problem where Machine 1 is the primary machine.

5. Conclusions and future research

In this study, we considered a problem in a two-machine re-entrant flow shop in which lot streaming is used for scheduling the single-job and multi-job cases separately. When Machine 1 or Machine 2 is the primary machine on which the third operation is performed, we proved that the single-job problem is polynomial-time solvable. We have also proved that the multi-job problem can be solved optimally when the third operation is performed on Machine 2. However, we have also proved that the multi-job problem is *NP*-hard when Machine 1 is the primary machine, machine so that we have developed a simple heuristic algorithm. To examine the effectiveness of our algorithm, we have developed a global lower bound on the makespan. The results of our computational experiments imply that our heuristic algorithm is quite effective in solving the multi-job problem optimally in reasonably short computational times.

Our study has some limiting assumptions for the problem under study. As in most studies in the lot streaming literature, we assume that the number of sublots of each job lot is known in advance. However, a more realistic case is when the problem's solution has to give its value along with the sublot sizes.

In our study, as in almost all of the previous studies in the literature, we assume that sublots in each job lot should be processed successively for each operation on each machine. i.e., we do not allow the intermingling of the job lots for the multi-job case. We may or may not obtain a better schedule by relaxing this assumption, but it is worth investigating.

Furthermore, in our study, sublot sizes may not be integral, so rounding them to the nearest integer numbers without violating the job-lot size may be needed. However, this approach may not provide the optimal makespan. Thus, this issue is also worthy of investigating.

Through our study for two machine and re-entrant flowshops, we hope that researchers working on scheduling problems will be aware that there is no study other than ours for scheduling with lot streaming in re-entrant manufacturing systems. Our study will open a new direction in the literature of scheduling with lot streaming since it is the only study that applies lot streaming for single- and multi-job cases in the re-entrant flow shops. We hope that our work will form a basis for developing algorithms to solve the scheduling problems in more complex re-entrant manufacturing systems where lot streaming is allowed.

There are several research extensions of this study that are open for future investigation:

- The assumption of knowing the number of sublots in advance could be relaxed, and investigating the problem under consideration without this assumption could be a future study issue.
- The sublot sizes obtained for the no-setup case studied in this paper may not be valid for the setup case The so that problem under consideration can be extended to a case where an issue with attached or detached setup is made before processing a job-lot.
- Our study assumes that sublots in each job-lot should be processed successively for each operation on each machine. i.e., we do not allow the intermingling of the job lots for the multi-job case. Relaxing this the no-intermingling assumption could be another future research issue.
- Our study could also be extended to the flow shops with more than two stages, having one machine at each stage, and a job lot may visit some stages more than once. and hybrid flow shops, which are the flow shops in which at least one of the stages has more than one machine, could also be studied.
- Different measures of performance rather than makespan could also be considered. For instance, the total completion time of sublots and job lots in the

single- and multi-job cases, respectively, could be a more relevant performance measure than makespan if the inventory holding costs are minimized.

Appendix A.

Proof of Theorem 1. As illustrated in the network representation given in Figure 1, a lower bound on the makespan $C_{\max}$, which is based on the first sublot, is given as the first sublot's processing time on M_1 plus the total processing time of all sublots on M_2, i.e., $C_{\max} \geq LB_1 = p_1 x_1 + (p_2 + p_3)(x_1 + x_2 + \ldots + x_s)$. Similarly, the total processing time of sublots 1 and 2 plus the total processing time of sublots 2 through s gives another lower bound, i.e., $C_{\max} \geq LB_2 = p_1(x_1 + x_2) + (p_2 + p_3)(x_2 + x_3 + \ldots + x_s)$. Similarly, we can write $C_{\max} \geq LB_i = p_1 \sum_{k=1}^{i} x_k + (p_2 + p_3) \sum_{k=i}^{s} x_k$ for each sublot $i = 2,\ldots,s$. It follows that $C_{\max} \geq \max_{1 \leq i \leq s} LB_i = \max_{1 \leq i \leq s} \left\{ p_1 \sum_{k=1}^{i} x_k + (p_2 + p_3) \sum_{k=i}^{s} x_k \right\}$. Thus, the linear programming model below can formulate the single-job problem where M_2 is the primary machine.

(P) Minimize $C_{\max}$ (A.1)

Subject to $C_{\max} \geq p_1 \sum_{k=1}^{i} x_k + (p_2 + p_3) \sum_{k=i}^{s} x_k$ for $i = 2,\ldots,s$ (A.2)

$\sum_{i=1}^{s} x_i = U$ (A.3)

$C_{\max} \geq 0$ (A.4)

$x_i \geq 0$ for $i = 2,\ldots,s$ (A.5)

Assuming that each of the inequalities in (A.2) is satisfied as equality, i.e., all sublots are critical to determining the makespan $C_{\max}$; we can obtain a feasible solution to problem P. In such a case, both M_1 and M_2 operate without idle time from one sublot to another, and the adjacent pair of sublots must satisfy the following relationship:

$$p_1 \sum_{k=1}^{i} x_k + (p_2 + p_3) \sum_{k=i}^{s} x_k = p_1 \sum_{k=1}^{i-1} x_k + (p_2 + p_3) \sum_{k=i-1}^{s} x_k \text{ for } i = 2,\ldots,s \quad \text{(A.6)}$$

or equivalently,

$$x_i = x_{i-1}(p_2 + p_3)/p_1 \text{ for } i = 2,\ldots,s \quad \text{(A.7)}$$

The idle time on M_2 is only before the first sublot, and it equals $p_1 x_1$. Then solving the set of simultaneous equations (A.3) and (A.7) yields

$$x_1 = U/(1 + \alpha + \alpha^2 + \ldots + \alpha^{s-1}), \quad \text{(A.8)}$$

$$x_i = \alpha^{i-1} x_1 \text{ for } i = 2,\ldots,s \quad \text{(A.9)}$$

where $\alpha = (p_2 + p_3)/p_1$.

Using (A.2), (A.3), (A.8) and (A.9), the makespan is obtained as

$$C_{\max} = p_1 x_1 + (p_2 + p_3)\sum_{i=1}^{s} x_i = (p_1 / (1+\alpha + +\alpha^2 + \ldots + \alpha^{s-1}) + (p_2 + p_3))\, U \,. \qquad \text{(A.10)}$$

We have shown that the solution given by the theorem is feasible. Note that this solution is the solution for the single-job lot streaming problem in the two-machine flow shop with processing times p_1 and $p_2 + p_3$ on M_1 and M_2, respectively.

Now, to prove the optimality of this feasible solution, the problem P may be re-written as

(P') Maximize $-C_{\max}$ (A.11)

Subject to $-C_{\max} + p_1 \sum_{k=1}^{i} x_k + (p_2 + p_3)\sum_{k=i}^{s} x_k \le 0$ for $i = 2,\ldots,s$ (A.12)

$\sum_{i=1}^{s} x_i = U$ (A.4)

$C_{\max} \ge 0$, $x_i \ge 0$ for $i = 2,\ldots,s$ (A.5)

The dual of (P') is constructed as

(D') Minimize $U\, y_0$ (A.13)

Subject to $p_1 \sum_{k=1}^{s} y_k + (p_2 + p_3)\sum_{k=1}^{i} y_k - y_0 \ge 0$ for $i = 2,\ldots,s$ (A.14)

$-\sum_{i=1}^{s} y_i \ge -1$ (A.15)

$y_i \ge 0$ for $i = 2,\ldots,s$ (A.16)

y_0 unrestricted in sign (A.17)

We can find a feasible solution to problem D' by assuming that all constraints defined in the dual problem D' are satisfied as equalities. It follows that a feasible solution to problem D' is achieved when

$$p_1 \sum_{k=1}^{s} y_k + (p_2 + p_3)\sum_{k=1}^{i} y_k = p_1 \sum_{k=i-1}^{s} y_k + (p_2 + p_3)\sum_{k=1}^{i-1} y_k \text{ for } i = 2,\ldots,s \qquad \text{(A.18)}$$

or equivalently,

$$y_i = y_{i-1} p_1 / (p_2 + p_3) \text{ for } i = 2,\ldots,s \,. \qquad \text{(A.19)}$$

Solving the set of equations in (A.18) and $\sum_{1 \le i \le s} y_i = 1$ simultaneously yields

$$y_1 = \alpha^{s-1}(1/(1+\alpha + +\alpha^2 + \ldots + \alpha^{s-1}))\,, \qquad \text{(A.20)}$$

$$y_i = \alpha^{1-i} y_1 \text{ for } i = 2,\ldots,s\,, \qquad \text{(A.21)}$$

$$y_0 = p_1 / (1+\alpha + +\alpha^2 + \ldots + \alpha^{s-1}) + (p_2 + p_3) \qquad \text{(A.22)}$$

where $\alpha = (p_2 + p_3)/ p_1$.

The objective function of the dual problem $D1'$ is obtained as

$$U\,y_0 = (p_1/(1+\alpha+\alpha^2+...+\alpha^{s-1}) + (p_2+p_3))\;U\,. \tag{A.23}$$

From equations (A.10) and (A.23), it is clear that the problem P' and its dual D' have the same objective function values. Thus, from the duality theory, it follows that equations (A.8)-(A.10) and (A.20)-(A.22) are the optimal solutions to the primal and dual problems, respectively. Therefore, we can conclude that the sublot sizes given in the theorem statement are optimal for the single-job problem where M_2 is the primary machine on which the third operation is performed. ■

Appendix B.

Proof of Theorem 3. For a job sequence π, let

[*j*] = job lot sequenced in the j th position of the sequence π,
$U_{[j]}$ = lot size of job lot [*j*],
$s_{[j]}$ = number of sublots of job lot [*j*],
i = index for sublots ($i = 1,...,s_{[j]}$),
$x_{[j],i}$ = size of the i th sublot in job lot [*j*],
k = index for machines ($k = 1,2,3$),
$p_{[j],k}$ = item (unit) processing time for the k th operation of job lot [*j*],
$C_{[j],i,k}$ = completion time of the k th operation for the i th sublot of job lot [*j*],
$RI_{[j]}$ = time lag between the start of the first operation on M_1 and the latest start time of the second operation on M_2 for job lot [*j*],
$RO_{[j]}$ = time lag between the completion times of the first and the third operations for job lot [*j*].

The completion time of the first operation for the i th sublot of job lot [*j*] is given by

$$C_{[j],i,1} = C_{[j],s_{[j-1]},1} + \sum_{r=1}^{i} p_{[j],1}x_{[j],r} \quad \text{for } i = 1,2,...,s_{[j]} \tag{B.1}$$

where $C_{[0],s_{[0]},1} = 0$. From equation (B.1), the completion time for the first operation of job lot [*j*], which is the completion time of the last sublot in this job on M_1, is obtained as

$$C_{[j],s_{[j]},1} = C_{[j-1]),s_{[j-1]},1} + \sum_{i=1}^{s_{[j]}} p_{[j],1}x_{[j],i} = C_{[j-1],s_{[j-1]},1} + p_{[j],1}\;U_{[j]}\,. \tag{B.2}$$

The completion time of the third operation for the first sublot of job lot [*j*] on M_2 is expressed as

$$C_{[j],1,3} = \max\left\{C_{[j],1,1},\; C_{[j-1],s_{[j-1]},3}\right\} + p_{[j],2}x_{[j],1} + p_{[j],3}x_{[j],1}$$

$$= \max\left\{C_{[j],1,1},\ C_{[j-1],s_{[j-1]},3}\right\} + (p_{[j],2} + p_{[j],3})x_{[j],1}\,. \tag{B.3}$$

Substituting $C_{[j],1,1}$ value from (B.2) into (B.3) yields

$$C_{[j],1,3} = \max\left\{C_{[j-1],s_{[j-1]},1} + p_{[j],1}x_{[j],1},\ C_{[j-1],s_{[j-1]},3}\right\} + (p_{[j],2} + p_{[j],3})x_{[j],1}\,. \tag{B.4}$$

Similarly, we may obtain the completion time of the third operation for the second sublot of job lot [*j*] on M_2 as

$$C_{[j],2,3} = \max\left\{C_{[j-1],s_{[j-1]},1} + \max_{1\le i\le 2}\left\{\sum_{r=1}^{i} p_{[j],1}x_{[j],r} - \sum_{r=1}^{i-1}(p_{[j],2} + p_{[j],3})x_{[j],r}\right\},\ C_{[j-1],s_{[j-1]},3}\right\}$$
$$+\sum_{i=1}^{2}(p_{[j],2} + p_{[j],3})x_{[j],i} \tag{B.5}$$

Repeating the process yields the completion time for the last operation of job lot [*j*], which is the completion time of the last sublot of this job lot on M_2,

$$C_{[j],s_{[j]},3} = \max\left\{C_{[j-1],s_{[j-1]},1} + \max_{1\le i\le s_{[j]}}\left\{\sum_{r=1}^{i} p_{[j],1}x_{[j],r} - \sum_{r=1}^{i-1}(p_{[j],2} + p_{[j],3})x_{[j],r}\right\},\right.$$
$$\left. C_{[j-1],s_{[j-1]},3}\right\} + \sum_{i=1}^{s_{[j]}}(p_{[j],2} + p_{[j],3})x_{[j],i}$$
$$= \max\left\{C_{[j-1],s_{[j-1]},1} + \max_{1\le i\le s_{[j]}}\left\{\sum_{r=1}^{i} p_{[j],1}x_{[j],r} - \sum_{r=1}^{i-1}(p_{[j],2} + p_{[j],3})x_{[j],r}\right\},\right.$$
$$\left. C_{[j-1],s_{[j-1]},3}\right\} + (p_{[j],2} + p_{[j],3})U_{[j]} \tag{B.6}$$

By successive application of (B.6) using (B.2), the time to complete the last job lot processed on M_2, $C_{[n],s_{[n]},3}$, is obtained as follows:

$$C_{[n],s_{[n]},3} = C_{\max} = \max_{1\le w\le n}\left\{\sum_{j=1}^{w} RI_{[j]} - \sum_{j=1}^{w-1} RO_{[j]}\right\} + \sum_{j=1}^{n}(p_{[j],2} + p_{[j],3})U_{[j]} \tag{B.7}$$

where

$$RI_{[j]} = \max_{1\le i\le s_{[j]}}\left\{\sum_{r=1}^{i} p_{[j],1}x_{[j],r} - \sum_{r=1}^{i-1}(p_{[j],2} + p_{[j],3})x_{[j],r}\right\}, \tag{B.8}$$

$$RO_{[j]} = \max_{1\le i\le s_{[j]}}\left\{\sum_{r=1}^{i} p_{[j],1}x_{[j],r} - \sum_{r=1}^{i-1}(p_{[j],2} + p_{[j],3})x_{[j],r}\right\} + (p_{[j],2} + p_{[j],3})U_{[j]} - p_{[j],1}U_{[j]}$$
$$= RI_{[j]} + (p_{[j],2} + p_{[j],3} - p_{[j]})U_{[j]} \tag{B.9}$$

Note that the second part, $\sum_{j=1}^{n}(p_{[j],2} + p_{[j],3})U_{[j]}$, in (B.7) giving the makespan value is a constant so that it is enough to minimize the first part, $\max_{1\le w\le n}\left\{\sum_{j=1}^{w} RI_{[j]} - \sum_{j=1}^{w-1} RO_{[j]}\right\}$, which is equivalent to the total idle time on M_2. Note that the first part is similar to Johnson's expression, where the processing times on M_1 and M_2 are replaced by the run-in and run-out delays, respectively. Therefore, job v precedes job z in an optimal schedule of job lots when $\min\{RI_v, RO_z\} \le \min\{RI_z, RO_v\}$. ■

Appendix C.

Proof of Theorem 4. It is clear that the minimizing the first term in (B.7), $\max_{1\le i\le s_{[j]}}\left\{\sum_{r=1}^{i} p_{[j],1}x_{[j],r} - \sum_{r=1}^{i-1}(p_{[j],2}+p_{[j],3})x_{[j],r}\right\}$, minimizes the makespan for a given sequence of job lots. In other words, sublot sizes minimizing the makespan for any arbitrary sequence (hence the optimal sequence) are identical to those sublot sizes which are determined by solving the sublot-sizing problem for each job lot separately. Therefore, the following linear programming model should be solved for every job lot in position [*j*]:

Minimize $Z_{[j]}$ (C.1)

Subject to $Z_{[j]} \ge \sum_{r=1}^{i} p_{[j],1}x_{[j],r} - \sum_{r=1}^{i-1}(p_{[j],2}+p_{[j],3})x_{[j],r}$ for $i = 1,2,\ldots,s_{[j]}$ (C.2)

$\sum_{i=1}^{s_{[j]}} x_{[j],i} = U_{[j]}$ (C.3)

$x_{[j],i} \ge 0$ for $i = 1,2,\ldots,s_{[j]}$. (C.4)

The optimal solution to this model is trivial due to its special structure. The minimum value of the objective function $Z_{[j]}$ is achieved when $Z_{[j]} = p_{[j],1}x_{[j],1}$ and the constraints in (C.2) are satisfied as equalities. Thus, the sublot sizes must be

$$x_{[j],i} = x_{[j],i-1}(p_{[j],2}+p_{[j],3})/p_{[j],1} = x_{[j],1}((p_{[j],2}+p_{[j],3})/p_{[j],1})^{i-1} \text{ for } i = 2,\ldots,s_{[j]}. \quad (C.5)$$

Substituting (C.5) into (C.3) yields

$$x_{[j],1} = U_{[j]}/(1+\alpha+\alpha^2+\ldots+\alpha^{s_{[j]}-1}), \quad (C.6)$$

$$x_{[j],i} = \alpha^{i-1}x_{[j],1} \text{ for } i = 2,\ldots,s_{[j]} \quad (C.7)$$

where $\alpha = (p_{[j],2}+p_{[j],3})/p_{[j],1}$.

Note that (C.6) and (C.7) are the same expressions as given in Section 3 for the single-job problem, and substituting (C.6) and (C.7) into (B.8) and (B.9) yields

$$RI_{[j]} = \max_{1\le i\le s_{[j]}}\left\{\sum_{r=1}^{i} p_{[j],1}x_{[j],r} - \sum_{r=1}^{i-1}(p_{[j],2}+p_{[j],3})x_{[j],r}\right\} = p_{[j],1}x_{[j],1}$$

$$= p_{[j],1}U_{[j]}/(1+\alpha+\alpha^2+\ldots+\alpha^{s_{[j]}-1}), \quad (C.8)$$

$$RO_{[j]} = RI_{[j]} + (p_{[j],2}+p_{[j],3}-p_{[j]})U_{[j]}. \quad (C.9)$$

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62

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