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Table of contents

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Intangible assets and the efficiency of manufacturing firms in the age of digitalisation: the Russian case

Yulia Turovets

ABSTRACT
A wide consensus exists on the role of intangible assets in both developed and developing economies, especially now, with the new generation of information and communication technologies. Emerging economies generally demonstrate lower endowment with intangibles (Dutz et al., 2012), but follow the same positive patterns for long-run development. In Russia, the contribution of intangibles to growth is still modest, and its capacity to foster productivity has not been achieved. As previous studies showed, efficiency represents one of the main channels of total factor productivity growth. This paper studies the effects of intangibles on the efficiency of Russian manufacturing firms in 2009–2018. Considering the heterogeneity of sectors and firms, the stochastic frontier model is applied. In general, the impact of intangibles is positive but small and influenced by external shocks and structural features. The paper provides evidence on different contributions of intangibles to efficiency for high-tech and low-tech firms and its change over time. It contributes to the strand of literature regarding the technical efficiency measurement on the microlevel. On the practical side, the paper suggests an analytical framework for differentiated policy mechanisms to drive investments in intangibles, which are essential for current digital transformation.

KEY WORDS
intangible assets, technical efficiency, manufacturing, digitalisation

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Introduction

Intellectual capital endowment becomes a fundamental prerequisite for technological advancements across countries and industries. Intangible assets (IA) have been considered a main source of productivity on an aggregate level during the last decades (Aghion & Howitt, 2006; Ramirez & Hachia, 2008; Chun & Nadiri, 2016; Montresor &Vezzani, 2013).

In developed economies, the marginal contribution of intangible capital to output growth already

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exceeds the physical one in high-tech production industries (Marrocu et al., 2012). According to Dal Borgo et al. (2013), manufacturing is among the sectors most heavily invested in intangible assets in the UK (manufacturing accounts for 51% of intangibles contribution to growth). In the French production sector, the growth in the share of intangibles also contributes to its enlargement in other industries (Delbecque et al., 2015). In Germany, the investment in intangible capital grew by 80-89% of the physical capital's level during 1995-2006 and half of the overall investment in intangibles accounted for manufacturing firms (Crass et al., 2014). Similar tendencies manifest in China, where sectors with a higher share of investment in intangible assets were the most productive between 1999 and 2007 (Fleisher et al., 2015).

Such upswing was largely driven by information and communication technologies (ICT), which clearly manifested in the U.S. where after 1995, the contribution of intangibles to the GDP growth was equal to that of physical assets (van Ark et al., 2008; Corrado et al., 2009; Nakamura, 2010). The IT revolution of 1994–2005 saw the most significant impact of intangibles on economic growth (Brynjolfsson et al., 2017). The famous Solow paradox, addressing the absence of the effect made by new technologies on productivity, has been widely discussed in the literature that offers a set of explanations and evidence (David, 1991; Brynjolfsson, 1993; Hatzius & Kris Dawsey, 2015).

Currently, economies undergo changes due to the new generation of ICT, induced by a drastic advancement in computing power (Furman & Seamans, 2018). Digitalisation is interpreted as an introduction or significant expansion of digital technologies in an organisation, a sector or the whole economy, leading to changes in business processes and significant socio-economic effects. This is expected to result in productivity gains (Tambe & Hitt, 2014; Dedrick et al., 2013; Aboal & Tacsir, 2018), structural changes (Bogliacino & Pianta, 2016; Rasel, 2017; Neirotti et al., 2018), new business models (Teece, 2018) as well as innovation intensification (Kleis et al., 2013; Sun & Li, 2017).

National governments encourage companies to adopt digital technologies and heavily support such initiatives. Russia represents a good example of such a policy. The national programme "Digital Economy of the Russian Federation" has been introduced in 2019 to secure the digital transformation in main sectors. Will these measures lead to gains? As intangibles become the core of the industrial process, it is important to consider its current role, patterns of influence on Russian enterprises, and industry-specific and idiosyncratic differences of the firms.

Due to the different nature compared to the physical capital, the IA impact on firms' performance shows distinct mechanisms and channels, which are widely discussed in the literature. They may result in technological change, efficiency improvement, production factor reallocation or capital deepening (Bresnahan & Trajtenberg, 1995; Kumbhakar & Lovell, 2000; Chun & Ishaq, 2016; Nwaiwu et al., 2020). From the innovation side, they foster within and across industries spillovers (Bontempi & Mairesse, 2015; Thum-Thysen et al., 2017; Pieri et al., 2018) and provide an interplay across different types of intangibles.

A large strand of literature is dedicated to analysing different IA types on macro, sectoral and micro levels. On a country-scale, authors use a growth accounting framework to measure the contribution of intangibles to labour productivity, the total factor productivity and the economic growth calculation (Corrado et al., 2009; Fukao et al., 2009; van Ark et al., 2009; Borras & Edquist, 2013; Adarov & Stehrer, 2009; Apokin & Ipatova, 2017; Corrado et al., 2013; Thum-Thysen et al., 2017; Chen & Krumwiede, 2017; Rylková & Šebestová, 2019; Soltysova & Bednar, 2015).

Among BRICS economies, the Russian case is the least researched. Shahabadi et al. (2018) used the Solow residual (Solow, 1957) to estimate the impact of different types of intellectual capital on total factor productivity (TFP) in emerging economies, including Russia, and conclude that this group of countries acquired existing new technologies rather than developed them.

Based on the existing macro estimates for Russia (Voskoboynikov et al., 2020), the effects of intangibles are not as large in comparison with developed countries. ICT, as the main asset in the age of digitalisation, contributes little to the TFP growth of in comparison to other physical elements (machines, buildings, etc.). On the other hand, ICT-growth rate in 2002–2007 was the largest in manufacturing as in most dynamic finance and services (Voskoboynikov et al., 2020). Arguably, the capacity of ICT and other intangibles in Russian manufacturing was not fully exploited opposite to developed economies, did not achieve a threshold and might serve as a productivity driver in the next decades.

Only several studies exist regarding the role of intangibles on Russian microdata, which support

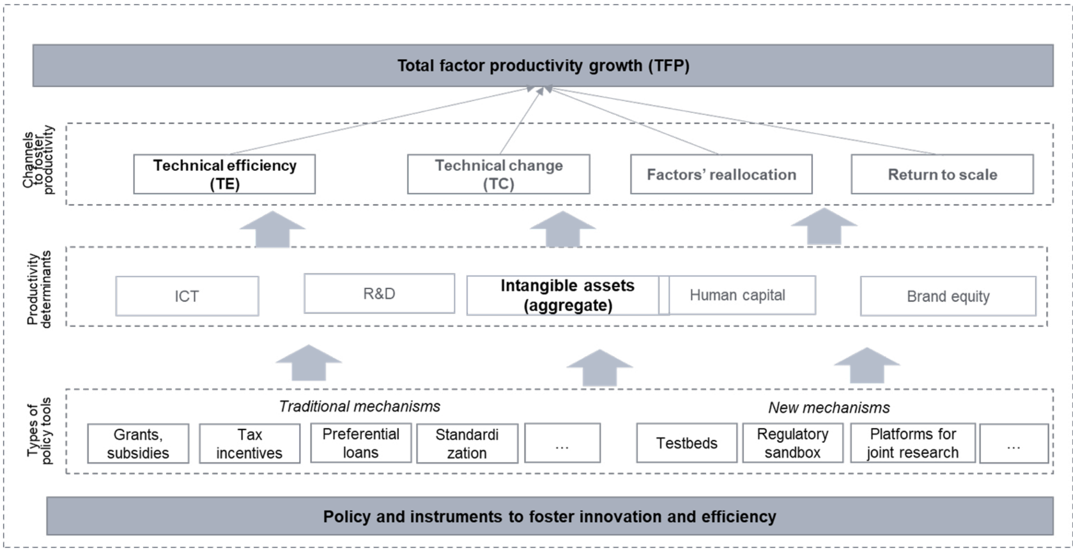

Fig. 1. Framework of the study in the context of productivity analysis

Source: elaborated by the author based on Kumbhakar and Fuss, 2000; Coelli et al., 2003; Corrado, Hulten and Sichel, 2005; Borras and Edquist, 2013.

evidence in the macrolevel. According to Shakina et al. (2014), a gap in intangibles is responsible for more than 26% of the variation in the gap in the economic value-added of Russian companies. Overall, the performance heterogeneity has a different scale of intangible capital in the firms (Molodchik et al., 2019). Several papers consider particular intangible assets and get similar patterns with other countries, particularly related to R&D and its link with technological change (Apokin & Ipatova, 2017; Pieri et al., 2018). Russian authors focus on company strategies for using IA (Shakina et al., 2016) and the taxonomy of firms based on this (Podmetina et al., 2011; Paklina et al., 2017), and addressing research and development in detail (Dezhina & Ponomarev, 2014; Simachev & Kuzyk, 2014; Gershman et al., 2018; Simachev & Kuzyk, 2019; Zemtsov et al., 2019).

According to previous results, efficiency was the main component of TFP, which has been affecting the productivity of industries since the end of 2000 (Ipatova, 2015) compared to the economic boom of 1998–2007 with a predominant role of the technological progress channel (Brock & Oglobin, 2018). Papers that refer to intangibles as an efficiency determinant of the level of firms are scarce. To close this gap, considering the evidence from the academic and empirical literature, this paper applied the stochastic frontier model (SFM) on the panel data for 2009–2018 of more than 300 public Russian companies from manufacturing industries. The following hypotheses were formulated: 1) intangibles positively affect technical efficiency and this effect increases over time; 2) IA with time become a major source of efficiency; 3) intangibles are more important for high-tech industries; and 4) its effects are reduced due to the crisis in 2014.

The paper is organised as follows. The first section briefly reviews the theoretical background of the paper. The second section reports on the empirical background. The third section describes the data of the study. The fourth section represents and discusses the results. The final fifth section gives policy implications and makes concluding remarks.

1. Theoretical background

This part overviews extant papers on IA and their relationship with productivity using microdata. This data-level enables using a broader set of intangibles concepts, variables and estimation techniques (Roth, 2019). To start, the outline of used IA definitions and that of the current study are given.

In financial accounting, an intangible asset is an object without a physical form that can bring economic benefits, when used in production activities for a long time. The academic literature considers intangible assets more broadly. They have key features, such as high value, a rarity for an organisation, complexity for imitation or substitution (Bontempi, 2016; Paklina et al., 2017). A comprehensive IA framework was proposed by Corrado et al. (2005) and is most often used in comparisons of countries and cross-countries. It includes research and development results, computerised information (software and databases), and economic competencies (particular characteristics of an individual firm, including personnel, trade names, etc.). An analysis is often stipulated by the availability and consistency of the data.

Most of the empirical results indicate a strong impact of IA on the efficiency of industrial companies regardless of country affiliation (Marrocu et al., 2012; Dal Borgo et al., 2013; Corrado et al., 2013; Goldar & Parida, 2017; Piekkola, 2020). Based on data of 1523 industrial enterprises located in key Chinese cities, Yang et al. (2018) found a significant positive relationship between the IA types (software, research and development, and organisational investment), and the performance of firms demonstrated differences in the relative importance of particular IA types compared with developed economies.

However, high investments in IA do not always lead to productivity growth: if a certain threshold is exceeded, further investments fail to generate positive effects. This relationship was found in public companies in Japan in 1991–2001 (Ramirez & Hachia, 2008). Companies from the industries of non-ferrous metallurgy and transport and telecommunications that reduced the volume of research and development, expressed in terms of capital stock, showed higher productivity. Two explanations are feasible: the IA distinct nature and lags to fully deploy and achieve effects. In general, IA act as a main source of productivity regardless of features particular to sectors and firms.

Long lags may lead to a negative impact on efficiency and productivity in the short term. Chappell & Jaffe (2018) found that IA investments lead to a decrease TFP caused by the time lag and cost growth of its implementation. Basu & Fernald (2007) obtained similar results when modelling the impact of ICT on industry productivity in the United States for 1987–2004. Short term investments may diminish TFP, as it needs time and resources for reorganisation and training. This lag can extend from 5 to 15 years. It also takes time to gain experience with a new production process. Over the long term, intangibles become particularly important for firms with initially low levels of productivity due to the catch-up effect (Heshmati et al., 1995; Castiglione & Infante, 2014).

The propensity to invest and the volume of investments in IA depend on internal characteristics of a particular firm, such as age and size, sector type and others (Marrocu et al. 2012; Goldar & Parida, 2017; Chappell & Jaffe, 2018; Yang et al., 2018). However, productivity is also strongly affected by external shocks. During these periods, even in the absence of significant changes in company strategies regarding IA, the rate of productivity growth may decrease (Tang & Wang, 2020).

Recent papers increasingly focus on the combination between different types of IA and its impact on performance through company innovation (Ramirez & Hachia, 2008; Kleis et al., 2012; Gómez & Vargas, 2012; Chun & Ishaq, 2016). Again, there is variation in the results. Montresor & Vezzani (2016) showed that IA is more important for the industry than internal research and development, which in turn is more important for the service sector. On the contrary, Ramirez & Hachia (2008) argued for a higher significance of internal R&D in manufacturing.

Thus, intangibles serve as an innovation factor (Hall et al., 2013), production factor (Corrado et al., 2009) or both (Pieri et al., 2018). Different types of IA may act as the first or the second category. Research is more important for innovation, while ICT — for productivity and efficiency (Hall et al., 2013); however, the former serves as a prerequisite of the latter two. Several papers also confirmed the role of R&D for efficiency gains (Ramirez & Hachia, 2008; Añón Higón et al., 2017; Shahiduzzaman et al., 2017). New waves of the literature suggest intangible assets contribute to service innovation in light of servitisation (Cheng & Krumwiede, 2017; Kozłowska, 2020) and business model transformation. Heterogeneity of results is often explained by individual characteristics of a firm (age, size, historical base of intangible assets, financial status, ownership, technology intensity, export status, and trade issues).

Based on the brief analysis, the IA assessment findings are rather diverse and depend on a large set of characteristics. This paper represents the first step to a wide analysis of IA features and trends in emerging countries on the example of Russian production companies.

2. Empirical approach

2.1. Model and method description

The empirical part of the research relies on the stochastic frontier model (SFM) as one of the most frequently used parametric methods in efficiency and productivity analysis (Coelli et al., 2003). The choice in favour of SFM is motivated by several reasons. According to Li (2009), production measurements are sensitive to selected techniques. Several studies have shown that the non-parametric DEA method can lead to unrealistic results, especially in a small number of observations and significant heterogeneity present in the current data. The key advantage of SFM is the absence of the assumption about the full efficiency of companies. Different levels of efficiency across companies, sectors, and countries explain the variation in TFP (Sharma et al., 2007). Moreover, in contrast to growth accounting and other non-parametric methods, SFM enables to reveal a causal relationship between productivity and various factors (Kılıçaslan et al., 2017).

SFM was firstly introduced by Aigner, Lovell and Schmidt (1977), and Meeusen and van den Broeck (1977), and ever since, it caught the attention of researchers in different domains, especially in the production analysis (Brasini & Freo, 2013; Chang et al., 2015). Conceptually, technical efficiency refers to the maximum achievable output with a given amount of input that changes under random (stochastic) forces (Farell, 1957). A frontier firm represents a best practice, which operates on the maximum available level of efficiency. A core feature of SFM is that it separates inefficiency from other random fluctuations and at the same time, it does not fix conditions between the elasticity of production and income shares (Castiglione, 2012).

A model for panel data was introduced by Kumbhakar & Sarkar (2003):

$$\ln y_{it} = \beta_{0t} + \sum_{j=1}^{k} \beta_j x_{it} + v_{it} - u_{it} \qquad (1)$$

where $\ln y_{it}$ — logged output, i=1,…, N — decision-making units (DMU), t=1,…T — time period, x_{jit}, j=1, …k — production inputs and other explanatory variables, v_{it} — exogenous stochastic noise, u_{it} — endogenous inefficiency error term.

Technical efficiency is closely tied with the productivity theory and contributes to TFP as one of the key transmission mechanisms (Pieri et al., 2018). When a firm improves its efficiency with existing technologies, it moves along the frontier. The adoption of new technologies may shift a frontier upwards due to technical change and transformation in the production process (Greene, 2008; Castiglione & Infante, 2014).

Inefficiency comprises two components of exogenous stochastic noise (v_i) and endogenous inefficiency error term (u_i) (Battese & Coelli, 1995; Kumbhakar & Lovell, 2000). The former is designed through heteroskedasticity equation, that might be estimated in one step by integrating it in production frontier or two-step approach, which means the consecutive estimation of two equations (Caudill & Ford, 1993; Battese & Coelli, 1995; Kumbhakar & Lovell, 2000). Consequently, factors can be studied that affect inefficiency and its intensity.

Most related studies use the translog specification of the stochastic frontier equation due to its flexibility and ability to measure the effect of changes in scale and allocative efficiency, as well as to identify time changing efficiency (Mattsson et al., 2020). However, several papers based on Russian data indicate the absence of an obvious advantage of the translog model over the Cobb-Douglas (Malakhov & Pilnik, 2013; Ipatova, 2015). Similar results were also obtained in the study by Shao and Lin (2002). Due to its simplicity, the Cobb-Douglas function represents a measurement of returns to scale and elasticity of substitution (Cardona et al., 2013).

SFM needs to impose distribution of error and technical inefficiency. It is assumed that the random error v_{it} is independent and identically distributed with zero mean and constant variance ($v_{it} \sim N(0, \sigma_v^2)$. The term u_{it} in the literature may have several types of distribution, while half-normal ($u_{it} \sim N+(0, \sigma_v^2)$) and truncated normal ($u_{it} \geq 0$, $\sim N+(\mu, \sigma_v^2)$) are most frequently used as indicators of time-varying technical inefficiency (Kumbhakar et al., 2017).

The current research uses panel data to discover the interplay between intangibles and inefficiency during ten years of accounting for the time trend. In the context of a broader approach of the TFP measurement, panel data enables to explore technical change as well and its evolution over time (Castiglione, 2014; Kumbhakar et al., 2017). The maximum likelihood method is used for estimation, as it is considered more informative than the general method of moments (Malakhov & Pilnik, 2013).

2.2. SFM in Russian Studies

Despite the wide use of SFM techniques, Russian researchers are discovering their advantages. There are several groups of papers that use SFM to examine inefficiency from different angles and factors. Manufacturing is the leader among the sectors investigated through a lens of SFM industries (Sabirianova et al., 2005; Ayvazyan et al., 2012; Mogilat & Ipatova, 2016). SFM was also used to estimate efficiency in banking (Kumbhakar & Peresetsky, 2013), non-profit organisations (Borisova et al., 2010) and some other industries.

Comparing different SFM models, three produce better results while considering heterogeneity and time trend: the four-error model, the True Random Effects (TRE) and time-variant models (TVD) (Malakhov & Pilnik, 2013). The level of data variability, the length of a panel, and the purpose of a study affect the choice of the appropriate model, but no single criterion applies in all cases. Shchetynin & Nazrullaeva (2012) obtained close results by testing five different models, starting from the basic one for panel data with constant (TI) and time-varying (TVD) technical efficiency. The most appropriate models with the distinguished inefficiency and individual effects are the true fixed-effects (Greene, 2008), the true random-effects and the model with four components (transient and persistent inefficiency) (Kumbhakar et al., 2014).

Different inefficiency patterns are attributed to a range of internal factors. Ipatova & Peresetsky (2013) used SFM to estimate the technical efficiency of production of rubber and plastic products. Controlling heteroscedasticity of the errors for 2006–2010, the authors focused on the return to scale and changes in technical efficiency during the crisis of 2008–2009. Both cross-sectional and panel data with Cobb-Douglas and translog specifications were tested for the sample of 1149 firms. It was shown that an increase in the size of a company raises its efficiency and return to scale. This result is robust for different functional types of production function and the evaluation method. In other words, the consolidation of enterprises may lead to the growth in average efficiency gains.

Shchetynin (2015) examined import effects on technical efficiency using SFM for the food industry. Four popular models were tested: time-invariant, time-variant, true random effects, and true fixed effects. The growth-share of import reduces technical efficiency but also results in a competition drop due to market concertation. Import growth helps to strengthen market positions of leading companies and hampers possibilities for the rest.

Several papers shed light on different determinants of technical efficiency. Krasnopeeva et al. (2016) investigated the impact of export status for manufacturing firms for 2004–2013. In doing so, they used two approaches based on SFM: the calculation of the marginal effect of the export status and the propensity score matching to compare similar exporting enterprises with non-exporters. Both approaches lead to the same result: the export effect does have positive implications. However, for the first approach, the average marginal effect for all industries and years was smaller and decreased after 2004. Technical efficiency and its marginal effect grow with the size of the firm.

Investments in fixed capital are another efficiency driver. Shchetynin & Nazrullaeva (2012) revealed a positive impact on the food industry in the period 2003–2010. While modelling the effects on cross-sectional and panel data, the translog specification is selected as more flexible possible changes in coefficients over time. The logarithm of investment in fixed capital with a year lag serves as inefficiency error; for the random error v_i a logarithm of labour costs was also applied. For those companies that invested in fixed assets in the previous period, the volatility of the inefficiency error was lower. Clustering firms by the number of employees they found that on average, technical efficiency estimates of the "true random-effects" model were somewhat similar in small and medium-sized enterprises. For large enterprises, the average value of technical efficiency was higher. In a model with two types of inefficiency (Kumbhakar et al., 2014), the distribution of technical efficiency estimates by clusters differed significantly. Overall, the results of modelling supported the hypothesis of a positive impact of investments; however, it is not always the case for the size. Technical efficiency of enterprises has gradually decreased since 2006. Large enterprises were the least affected during the crisis of 2008, they underwent a 2% decline in efficiency in 2010, while in the small and medium-sized enterprises, technical efficiency decreased by almost 7%.

SFM is also used as one of the parametric techniques to measure TFP in a number of papers. Ipatova (2015) provided evidence on the efficiency patterns for medium-tech industries and particularly for production of plastics and its TFP. On the panel of 2006–2012, SFM and DEA were applied for the efficiency measurement and robustness check. Differently than in other studies, Cobb-Douglas was chosen instead of translog, as there was no significant difference in the results. To compare the results of two models, the author used the Pearson correlation coefficient and the Spearman's rank correlation coefficient. Both DEA and SFM gave similar rankings of the firms, but the technical efficiency was different for the quantile groups of firms. The first quarter of the most productive firms demonstrated a positive trend in TFP and technical efficiency. Other 25% of firms were close to the level of 2006, and the remaining half of the sector showed weak results. Among different TFP components examined in the study, the technical efficiency demonstrated the highest variation and a drop in 2009. Its contribution and a technical change played the central role in TFP growth.

Apokin and Ipatova (2017) calculated TFP using SFM combined the Malmquist productivity indices with a technical efficiency component. Using the data of OECD countries and Russia for 1990–2010, they found that a higher TFP level was associated with a lower growth rate in the next period. Private R&D expenses were a significant factor for TFP growth, but with a lag of five years. However, for Russia, this influence was less due to a smaller share of private expenses in comparison with state expenses in the overall amount of R&D expenses.

Based on the description above, intangibles are not yet discovered as efficiency determinants; however, some studies account IA as a performance driver (Shakina et al., 2016; Molodchik et al., 2019).

3. Data and research design

This paper uses data from the Ruslana database for 340 public companies belonging to the economic activities listed under codes 10–33 OKVED2 (synchronised with the NACE classification). The time span covers 2009–2018 and includes 3310 observations. This category of companies makes a crucial contribution to productivity and overall investment. Previously, Paklina et al. (2017) also studied listed companies and assessed their strategic choices regarding intellectual capital.

Output as a dependent variable is presented by the operating revenue of companies. The number of employees (l) is measured in persons, while other explanatory variables, including fixed assets (fa), other assets (asset), intangible assets (ita), in thousands of Russian roubles. All monetary variables are nominated in constant prices of 2009 and deflated using the GDP index-deflators, which are calculated by the national statistical office and available on the website of the statistical office.

The main limitation of the study is the absence of data on ICT-capital at the level of firms. The aforementioned database contains data on R&D capital, but with numerous omissions that hamper estimation. To assess the intellectual capital of companies as a whole, the aggregate indicator of intangible assets is presented in the annual financial statements of the firms. IA has been previously shown as an adequate variable in the stochastic frontier exercises for Russian firms (Ayvazyan et al., 2012). According to the national accounting system, intangible assets comprise patent and other intellectual property on inventions, licenses on software and databases, trade names, as well as goodwill (KPMG, 2012).

As cited earlier, the Cobb-Douglas specification with logged values is chosen for Russian data. It is expressed as follows:

$$\ln y_{it} = \beta_0 + \beta_1 t + \beta_2 \ln fa_{it} + \beta_3\, ln\, asset_{it} + \\ + \beta_4 ln\, ita_{it} + \beta_5 lnl_{it} + v_{it} - u_{it} \qquad (2)$$

where $ln\, y_{it}$— turnover of the company i in period t, t — years, $ln\, fa_{it}$ — fixed assets as proxy for capital, $ln\, ita_{it}$ — intangible assets, $ln\, l_{it}$— number of employees, v_{it} — stochastic noise, u_{it} — technical inefficiency. To include fixed capital that is rented by a company, and based on Ipatova & Peresetskiy (2013) and Shchetynin (2017), other assets ($ln\, asset_{it}$) are inserted in the model.

In this class of stochastic models, technical efficiency changes under determinants specified in the heteroskedasticity equation (Pieri et al., 2018). There are two determinants in the current study: intangible assets and the time trend. Intangibles also contribute to TFP due to the accumulation with time and technical change, which is embedded in the time trend t in the production frontier equation. The heteroscedasticity equation is defined as:

$$\log\,(\sigma_{uit}) = \delta_0 + \delta_1 ln\, ita_{it} + \delta_2 t \qquad (3)$$

where δ_n— estimated coefficients of technical efficiency determinants.

Following Pieri et al. (2018), it is assumed that TFP is influenced by the trend (t), intangible assets ($ln\, ita_{it}$), its evolution in time ($\rho_2 t \times ln\, ita_{it}$) and technical inefficiency (u_{it}):

$$tfp_{it} = \rho_0\, t + \rho_1 ln\, ita_{it} + \rho_2 t \times ln\, ita_{it} - u_{it} \qquad (4)$$

where ρ_n — estimated coefficients of TFP determinants.

Along with this, the time trend is usually interpreted as TFP in more common models for panel analysis (the time-variant model). To compare the trend attitude, two other specifications are applied: time-variant and time-invariant models. The first one estimates technical efficiency for each year separately. Such a model focuses on persistent inefficiency and does not require distributional assumptions (Kumbhakar et al., 2014). It has the following form:

$$\ln y_{it} = \beta_0 + \beta_1 \ln fa_{it} + \beta_2 ln\, asset_{it} + \\ + \beta_3\, ln\, ita_{it} + ln_4\, l_{it} + d\, year_{it} + v_i - u_i \qquad (5)$$

where $d\ year_{it}$ means dummy variables for each of ten years, other variables are the same as stated earlier. In contrast to the specification indicated in equation (2), the time-variant decay model assumes v_i and u_i to be independent. It also implies that there is a trend in inefficiency error, which is estimated in the following way (Kumbhakar & Lovell, 2000):

$$u_{it} = \left(-\exp\left(-\eta(t - T_i)\right)\right)u_i \qquad (6)$$

where Ti — the last year in the panel, η — the decay parameter, errors v_{it} are independent and identically distributed with zero mean and constant variance ($v_{it}{\sim}N(0, \sigma_v^2)$, u_{it} is the base-level inefficiency (the level of inefficiency for firm i in the last period T_i) that follows truncated normal distribution ($u_i{\sim}N^+(\mu, \sigma_u^2)$), v_{it} and u_i are distributed independently. This helps to distinguish different patterns in trend and further discuss its possible reasons.

4. Empirical results

4.1. Intangibles and efficiency

This section presents the main results of the empirical analysis. As a preliminary step, it is checked whether SFM is an appropriate tool for efficiency estimation. In doing so, a simple regression model is estimated with an analysis of residuals distribution. It confirms the presence of heterogeneity and, thus, justifies the choice for SFM.

Main results are shown in Tables 1 and 2. The first contains the results of the estimation for the full sample of the firms. Four major models are tested. Model 1 demonstrates the estimation of the model without inefficiency determinants. Technical inefficiency induced by intangibles and the time trend is introduced in Model 2. Model 3 and 4 analyse effects before and after 2014. This year is marked as the cur-

Tab. 1. Panel Estimation of the Stochastic Production Frontier for the full sample of firms

	Model 1 (stochastic frontier without inefficiency determinants)	Model 2 (stochastic frontier with inefficiency determinants)	Model 3 (stochastic frontier with inefficiency determinants before 2014)	Model 4 (stochastic frontier with inefficiency determinants after 2014)
1. Production frontier (dependent variable ln_y)				
Number of observations	2,915	2,915	1,381	1,534
ln_fa_real	0.106*** (0.007)	0.106*** (0.007)	0.124*** (0.011)	0.096*** (0.009)
ln_assets	0.347*** (0.013)	0.354*** (0.013)	0.325*** (0.019)	0.381*** (0.018)
ln_l	0.561*** (0.016)	0.557*** (0.017)	0.507*** (0.026)	0.591*** (0.023)
ln_ita_real	0.019*** (0.006)	-0.011* (0.007)	-0.018 (0.011)	-0.023 (0.017)
t	0.016** (0.006)	0.017* (0.009)	0.008 (0.031)	0.082*** (0.024)
ita_t	-0.003*** (0.001)	-0.003*** (0.001)	-0.004 (0.004)	-0.001 (0.003)
const	4.732*** (0.136)	4.753*** (0.135)	5.294*** (0.201)	3.758*** (0.242)
2. Inefficiency equation (dependent variable)				
ln_ita_real_t		-0.108*** (0.011)	-0.178*** (0.021)	-0.065*** (0.013)
t		-0.002*** (0.016)	-0.177*** (0.066)	0.235*** (0.051)
const	0.072 (0.048)	0.362 (0.084)	0.806*** (0.137)	-1.583*** (0.403)
3. Stochastic noise (dependent variable)				
const	-1.495*** (0.058)	-1.424 (0.014)	-1.336 (0.074)	-1.447 (0.094)

Note: *, **, * * * — significance at 10%, 5%, and 1% levels, respectively; standard errors are shown in parentheses.

rency crisis and, according to the existent papers, should be the watershed in terms of efficiency and its changes (Bessonova, 2018).

Model 1 gives a general overview of the production frontier. Intangibles positively affect output; however, this value is still modest. The same is true for the time trend, which is interpreted as TFP in this specification. It means that during the period, an average firm in the sample improves its productivity. However, with time, intangibles produce a rather small effect on the production output. Such a result might be explained in several ways. Since intangible assets are expressed as accumulated capital (Corrado et al., 2009), it should depreciate and wear out, just as the physical does. Then, there is a need to update it and to expand its volume (Corrado et al., 2009; Bontempi & Mairesse, 2015). Capitalised intangibles as an aggregate indicator are an important factor for productivity. As determined by Bontempi & Mairesse (2015), capitalised assets give better results compared to those measured in costs, as conceptually they represent time-changing stock. Current results indicate that companies invest insufficiently in this type of assets. This statement is supported by sectoral statistics. Machines are considered the main source of innovation in manufacturing, and this trend has remained rather stable during the last decades (Gokhberg et al., 2020).

Model 2 has explicit efficiency determinants. There is a raise in the time trend for the end of the period, and its value is larger than in Model 1. The trend is small, but significant for efficiency improvement. Intangibles in Model 2 equation reduce technical inefficiency, as the corresponding coefficient is negative and strongly significant. By splitting the sample before and after 2014, one may see that the IA role as a production factor is not steady during the period. The declining trend is visible in the heterogeneity equation. Before 2014, the IA contribution to inefficiency was stronger (-0.18) than later (-0.07). This suggests that the positive process that started to emerge and previously gave positive outcomes, but is hampered by the crisis that corroborates the effects of several years. However, with time, the trend became positive and increased the output to roughly 1%. Why 2014 induces such unfavourable consequences for the companies? This year is associated with more expensive foreign technologies. This fact, however, is two-sided: on the one hand, firms were forced to develop solutions domestically and modify technological strategies. On the other hand, firms were unprepared for such a drastic change and suffered losses in the short run to adjust their behaviour (Bessonova, 2018). This influence was not the same across the sample.

Table 2 provides estimation for two groups of firms according to their R&D expenditures (firms that either invest in R&D and not) and the R&D intensity of the sector (firms that belong to high-tech and low-tech sectors), as manufacturing industries are very different in terms of technologies and resources used for innovation.

It is useful to indicate the patterns developed in these sub-groups of firms and how they differ from each other. For the sample of firms with R&D expenditures, intangibles affect technical inefficiency more than for those without, (-0.13) and (-0.1) accordingly. When considering high and low-tech industries, the results show the same patterns ((-0.26) and (-0.16) accordingly) and its the scale is bigger. The scale in the effect of intangibles on the inefficiency is biggest for the firms from high-tech sectors than for firms with R&D expenditures. One possible explanation is the systemic activities for knowledge accumulation that lead to additional gains from intangibles use in high-tech firms. This means that on average, such firms perform better and some complementarity between aggregate intangibles and systemic R&D activities may exist. A systemic activity for knowledge accumulation leads to additional gains from intangibles use in high-tech firms.

The effects of the trend are observed when considering the sub-sample of companies according to R&D expenditures. For these firms, the role of intangibles is more evident for the overall performance. To foster production, they rely more on IA that results in the technical change and shift of a frontier rather than gains in efficiency (Pieri et al., 2018). Firms without R&D do not seek to move the frontier upward and often use intangibles developed externally. The main channel of intangibles for them is tied with efficiency, not technical change and TFP (Bonanno, 2016; Kılıçaslan et al., 2017; Pieri et al., 2018).

Figs. 2–4 illustrate the distribution of technical efficiency for the full sample, and for two types of sectors, namely, high-tech and low-tech. It is obvious that low-tech firms reflect the higher distribution of efficiency, and generally, its level is smaller than in high-tech sectors, as well as dispersion. Higher variation of inefficiency means that companies have different patterns, and it is assumed that a group of leaders exists in both groups, and they do not approach each other. In other words, more efficient firms became even more efficient and enlarged the gap with the laggards.

The inefficiency dynamic shows several points to discuss (Fig. 5). Considering inefficiency changes over time, there is strong evidence that after a crisis year, the level of its spread should expand. The results suggest that the drop in efficiency appeared even earlier in 2013 and remained after 2015. This confirms that along with external shocks, more structural issues are responsible for the efficiency decline. The patterns are distinct for high- and low-tech firms. The latter underwent a larger drop in efficiency in 2015. In comparison with high-tech, its level is lower on average. It is important to note that technical effi-

Tab. 2. Panel Estimation of the Stochastic Production Frontier for sub-samples of firms by R&D expenditures and R&D intensity

	Model 5 (stochastic frontier for the firms of high-tech sectors)	**Model 6 (stochastic frontier for the firms of low-tech sectors)**	**Model 7 (stochastic frontier for the firms with R&D expenditures)**	**Model 8 (stochastic frontier for the firms without R&D expenditures)**
Production frontier (dependent variable ln_y)				
Number of observations	1,472	1,443	734	2,181
ln_fa_real	0.106*** (0.017)	0.112*** (0.007)	0.109*** (0.013)	0.076*** (0.007)
ln_assets	0.426*** (0.028)	0.332*** (0.015)	0.350*** (0.016)	0.397*** (0.019)
ln_l	0.599*** (0.034)	0.552*** (0.02)	0.531*** (0.023)	0.522*** (0.025)
ln_ita_real	-0.120*** (0.026)	-0.021*** (0.009)	-0.019** (0.009)	0.008 (0.008)
t	0.004 (0.048)	-0.015 (0.009)	0.026* (0.013)	0.021** (0.009)
ita_t	0.003 (0.004)	0.001 (0.001)	-0.0001 (0.001)	-0.004*** (0.001)
const	4.021*** (0.377)	5.082*** (0.149)	4.838*** (0.190)	4.922*** (0.17)
Inefficiency equation (dependent variable)				
ln_ita_real_t	-0.262*** (0.046)	-0.158*** (0.018)	-0.125*** (0.016)	-0.102*** (0.012)
t	0.296*** (0.057)	-0.112*** (0.023)	-0.008 (0.023)	-0.036*** (0.021)
const	-0.030 (0.495)	0.668*** (0.096)	0.373*** (0.119)	0.445*** (0.10)
Stochastic noise (dependent variable)				
const	-1.568 (0.111)	-1.315 (0.017)	-1.336 (0.065)	-2.082 (0.018)

Note: *, **, * * * — significance at 10%, 5%, and 1% levels, respectively; standard errors are shown in parentheses.

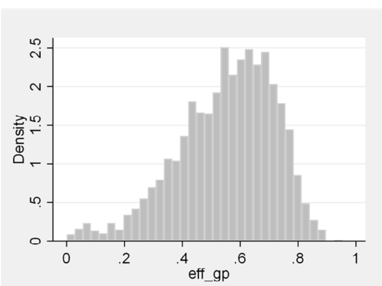

Fig. 2. Distribution of technical efficiency for the full sample with inefficiency determinants

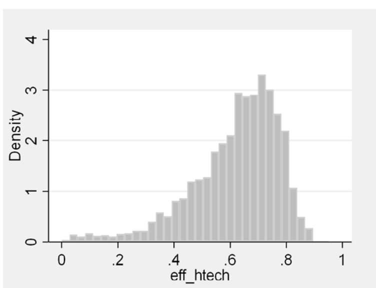

Fig. 3. Distribution of technical efficiency for the firms from high-tech sectors with inefficiency determinants

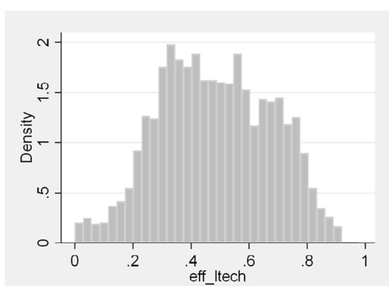

Fig. 4. Distribution of technical efficiency for the firms from low-tech sectors with inefficiency determinants

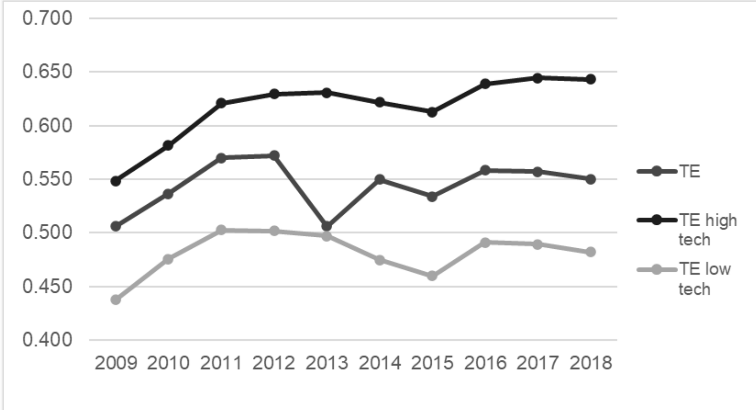

Fig. 5. Average technical efficiency dynamic in 2009–2018 for the full sample model

Note: TE — technical efficiency for the full sample, TE high-tech — technical efficiency for the firms of the high-tech sectors, TE low-tech — technical efficiency for the firms of the low-tech sectors.

ciency is a relative indicator and should be interpreted only in terms of ranking and its changes. Overall, the scale of technical efficiency, as expected, is stronger for high-tech industries. Studies for different countries also confirm such relationships (e.g., Crass et al., 2014; Añón Higón et al., 2017; Goldar & Parida, 2017; Piekkola, 2019).

4.2. Time trend analysis

To verify how trend and efficiency behave without intangibles as inefficiency driver, the paper analyses several sub-samples with time-variant (TI) and time-invariant (TVD) models, which also checks the robustness.

Table 3 shows the main results for the estimation of the impact made by the crisis year considering its changes and implications for firms of high- and low-tech groups. Different models — the frontier model without trend and inefficiency determinants and the time-variant model (TVD), which is more common for panel data and shows trends and technical efficiency changes — revealed a large difference and time-dependent change.

The significance of the years' coefficients is also tested. After 2014, high-tech firms experienced a reduction in production. In terms of the time trend, they performed better in 2011–2013. On the contrary, no significant changes were observed for low-tech firms for ten years. For the former, such a result is also revealed in Section 4.1 in the models with efficiency determinants, in contrast to high-tech firms. It means that a positive pattern started to emerge before the crisis and stopped in 2014. In 2014, import machines and equipment became more expensive and less available due to the national currency depreciation. As high-tech firms usually are more sensitive to import changes, they tried to substitute foreign technologies by developing them domestically (Simachev et al., 2019). It requires large resources that are taken away from current production and results in a decrease in output in the short run. In the medium run, the overall effect remains negative till 2018. This reasoning goes in line with past research in the field (Apokin & Ipatova, 2017). Due to enlarged spread across the firms in terms of inefficiency, an average firm did not succeed to grow, even though the frontier moved upwardly.

By further applying the TVD model for sub-samples, a certain improvement in the output of low-tech firms is revealed, but inefficiency increased as well. It means that productive firms operate even better over time, while the laggards perform worse. The high-tech firms demonstrated the same pattern: technical inefficiency (the negative sign of the *eta* variable in Table 3) increased despite the trend growth, which is expected to result in negative growth for an average firm in the group.

A closer look at the period after 2014, which is the point of interest, reveals that trend changes, as well as efficiency *(eta)*, affected mostly the low-tech group. On the contrary, for companies from high-tech industries, the impact did not change significantly: almost the same contribution to reduction of inefficiency (-0.042) and production growth (0.014).

However, due to inefficiency expansion, the firms did not seize opportunities that opened with the frontier shift. Only a tiny group of companies improved their production possibilities. Due to difficulties with the technology transfer, companies were forced to seek other sources of technological solu-

Tab. 3. Estimations of time-invariant (TI) and time-variant (TVD) models by the two time periods and the groups of firms

	Model 1 TI-model without trend and inefficiency determinants for high-tech firms	Model 2 TI-model without trend and inefficiency determinants for low-tech firms	Model 3 TVD-model for high-tech firms	Model 4 TVD-model for high-tech firms after 2014	Model 5 TVD-model for low-tech firms	Model 6 TVD-model for low-tech firms after 2014
Production frontier (dependent variable ln_y)						
Number of observations	1,472	1,443	1472	770	1443	764
ln_fa_real	0.107*** (0.014)	0.073*** (0.007)	0.064*** (.018)	0.076*** (0.010)	0.047*** (0.016)	0.033** (0.014)
ln_assets	0.339*** (0.016)	0.430*** (0.019)	0.294*** (0.027)	0.462*** (0.029)	0.42*** (0.028)	0.311*** (0.030)
ln_l	0.552*** (0.023)	0.483*** (0.024)	0.642*** (0.038)	0.450*** (0.038)	0.558*** (0.032)	0.522*** (0.033)
ln_ita_real	0.010*** (0.004)	0.014*** (0.003)	0.014*** (0.005)	0.014*** (0.005)	0.004 (0.005)	0.005 (0.006)
t			0.071 (0.045)	0.039*** (0.008)	0.234*** (0.031)	0.016 (0.014)
const	4.542*** (0.202)	4.729*** (0.186)	6.148 (0.651)	4.281*** (0.284)	2.920*** (0.318)	6.878*** (0.336)
eta			-0.047** (0.019)	-0.042*** (0.012)	-0.240*** (0.022)	0.001 (0.012)
	-1.373*** (0.067)	-2.219 (0.102)				
	-0.136** (0.070)	0.116 (0.056)				

Note: *, **, * * * — significance at 10%, 5%, and 1% levels, respectively; standard errors are shown in parentheses.

tions, which, firstly, delayed production and, secondly, required the transformation in supply chains. Again, this goes in line with the literature that indicates that internal innovation activities have lagged effects and require time for accumulation to result in the output growth (Aghion & Howitt, 2006; Ramirez & Hachia, 2008, 2008).

To sum up, intangibles reduced the inefficiency, and this result was robust across time and groups of firms. After 2014, the IA impact reduced for the full sample, and at the same time, trend contributed positively to the overall output. Firms that belong to high-tech industries receive a greater IA effect on technical efficiency due to the existence of certain complementarity across different types of intangibles and stable accumulation of knowledge (Gómez & Vargas, 2012; Piekkola, 2019). However, testing intangibles impact on inefficiency with the simple time-variant model shows greater effects for low-tech firms. This may indicate that the models with heteroskedasticity equation are more suitable for measuring the relationship of intangibles and technical inefficiency. The finding represents an area for further exploration.

5. Suggestions for policy mechanisms to foster investments in intangibles

How to stimulate firms to invest in intangibles? Company incentives to invest in transformation and implement related complementary changes are largely affected by the policy to promote technology adoption, and this trend is stable across developed and emerging economies (Teece, 2018). Despite differences in the scope and direction of policies, almost all governments offer such support. It is not surprising that the industry receives attention, especially in times of crisis, when the modernisation of production becomes a factor of survival (Shakina & Barajas, 2016; Polder et al., 2018).

This statement is supported by the recent global crisis in 2008–2009. A trend was observed in developed economies to establish specialised institutions for the development and dissemination of advanced manufacturing technologies. Such initiatives were launched in the United States (sine 2011, the programme "Manufacturing USA"), the United Kingdom (since 2013, catapult centres), Australia ("Industry 4.0 Testlabs for Australia"), Canada (the Advanced Manufacturing Supercluster), Japan (Smart Manufacturing — Smart Monozukuri initiative), South Korea (manufacturing innovation centres 3.0) (GOV.UK, 2017; Australia Prime Minister's Industry 4.0 Taskforce, 2017; METI, 2017; Next Generation Manufacturing Canada, 2018; GAO, 2019). Most of these initiatives promote an advanced class of technologies, including computer modelling, new material development, production systems etc. that are expensive and need business restructuring (Nazarko, 2017).

Current trends in sectoral technological development are induced by the next wave of information and communication technologies (ITU, 2017; Brynjolfsson et al., 2017). Though the channels of technology dissemination and influence on production performance are common, digitalisation varies due to differences in countries and characteristics of firms. In emerging economies, productivity is frequently driven by the acquired and imported technologies, embodied in machinery and software. In general, they serve as a leading mechanism to promote innovation activities compared to domestic R&D in developed countries (Shahabadi et al., 2018). Recent studies show that the growth of ICT plays a key role in the TFP increase in emerging economies due to larger investments compared to other intellectual assets and primarily R&D (Shahabadi et al., 2018). In search of new innovation sources, digitalisation may play a role as a factor for production efficiency and the development of new products (Paklina et al., 2017).

To find appropriate triggers in sectors, a range of new policy mechanisms arises with the implementation of traditional ones. They contribute to narrowing the digital gap across and within sectors (Spiezia, 2011; Polder et al., 2018). The set of new tools comprises "living labs" (e.g., for driverless cars in Germany), testbeds (for blockchain technologies in the Republic of Korea) or platforms for joint research. Regulatory sandboxes is a relatively new tool that plays a particular role in industry absorbing new solutions. For example, special regimes help to test unmanned aerial vehicles in the US, or unmanned road vehicles in Germany (Federal Aviation Administration, 2018; BMWi, 2020). Many such initiatives address SMEs, including technology transfer, assistance with finding partners, and financial support (BMWi, 2019). Specialised platforms for small firms from different sectors provide an opportunity to choose an appropriate financial tool and receive professional consultation on digitalisation (France NUM, 2020).

Instruments aimed at promoting the demand for digital technologies also differ. Flexible fiscal mechanisms are applied to promote the mass adoption of technologies among companies. They cover a wide range of economic agents and include an accelerated depreciation or tax credits for investments in information technologies etc. Along with soft loans for buying digital products and services, various vouchers were actively used to support SMEs, including those focused on innovation (European Commission, 2018). Standardisation and certification is another area of interest to support the technology dissemination on a massive scale. Along with it, the entrepreneurship infrastructure, methodological recommendations for digital transformation, market regulation and other existing tools represent a large area for policymakers (OECD, 2017).

Aiming to maximise efforts of different decisions, requires them to be targeted in terms of sectoral problems and features, including efficiency and productivity issues. This is especially critical in the current times marked by the coronavirus crisis and challenges faced by countries. The national programme "Digital Economy of the Russian Federation" goes in line with the foreign initiatives and provides many mechanisms to support the adoption and use of digital technologies. The initiatives resemble those in other countries, where manufacturing is among the priority industries.

Results of the previous section suggest that intangibles do play an important role in decreasing the sectoral technical inefficiency. It is expected that intangibles in the short and medium run will secure an efficient production process, and later, it will contribute to the channel of innovation via the technological shift. Based on this reasoning, an analytical framework to choose policy instruments is introduced (Table 4).

Policy initiatives to promote digitalisation should be different due to sectoral R&D intensity and strategies to adopt digital technology, i.e., to develop or acquire. From this perspective, companies may introduce existing or new technologies. Several sets of policy tools can be distinguished. The number of R&D support tools is limited because of a risky

Tab. 4. Strategies and policy tools to support digitalisation according to the technology intensity of firms

	High-tech firms	Low-tech firms
Develop an intangible technology asset	*Effects* Frontier shift ++ Efficiency change - *Policy tools* Grants Venture capital Tax incentives Preferential loans Standardisation Testbeds Regulatory sandbox	*Effects* Frontier shift + Efficiency change + *Policy tools* Grants Tax incentives Preferential loans Standardisation Testbeds
Acquire an intangible technology asset	*Effects* Frontier shift - Efficiency improvement ++ *Policy tools* Tax incentives Preferential loans Technology transfer centres Guidelines and information platforms	*Effects* Frontier shift + Efficiency improvement ++ *Policy tools* Tax incentives Preferential loans Technology transfer centres Guidelines and information platforms

Note: The highlighted cells represent the largest effects for high and low-tech sectors; "+" reflects the intensity of the influence on technical efficiency or technical change (the frontier shift).

nature; however, they imply the most extensive effects in terms of efficiency and technical change. Low-tech firms that provide R&D obtain the same results, but they are less significant than high-tech. Again, a less intensive impact resulted from the acquisition of technological assets in low-tech firms. On average, it results in more considerable efficiency gains and is supported by instruments (tax incentives, preferential loans, transfer centres, etc.) that are expected to spread technologies in a large group of companies.

It is assumed that digital asset accumulation correlates with innovation capacity (Hall et al., 2013; Borgo et al., 2013; Añón Higón et al., 2017; Ejdys, 2020). Since then, an average firm has two alternatives: to develop a solution in-house or in cooperation with partners, including universities and scientific organisations. It may also choose acquisition from an external supplier. The previous studies found that high-tech firms more often adopting customised technological solutions or developing them in cooperation with external suppliers (Pieri et al., 2018). The opposite is true for low-tech firms, which frequently implement existing technologies. To support the development of new intangible assets, decision-makers may opt for more risky measures, such as venture capital, testbeds or regulatory sandboxes. The development of new technologies should reconcile with the elaboration of standards that offer new technical rules. When it comes to new solutions, the number of organisations is often limited, and in this case, grants or subsidies may be the most efficient way to stimulate innovation. As more firms get engaged in R&D, measures having a wider coverage are required, such as tax incentives (e.g., income tax relief for R&D activities). For all categories, regulation plays a central role as an enabler of legal conditions for technology adoption and use.

The acquisition has a relatively lower impact on productivity but may still result in the frontier shift. Policy instruments are less risky and aim to involve a larger number of firms. In the case of the purchase of new assets, a business often needs guidelines, frameworks and general information on new technological issues. Both for high-tech and low-tech groups, a similar set of instruments may be applied. The initial idea of such support is to smooth differences in technological capacities and stimulate within and across industry spillovers.

The reasoning presented in this section represents a starting point to a further, more detailed investigation of types of intangibles and the scale, to which they affect manufacturing companies in Russia. Here, only some general vision is developed. Such an approach enables better planning and assessment of technological development in organisations (Bieńkowska, 2020; Nazarko et al., 2020). Next research may address the empirical estimation of different types of intangibles and the impact associated with this policy instrument on the propensity of companies to accumulate intangibles. This may bring useful insights into fostering investments in intangibles and, particularly, digital technologies.

Conclusions

The role of intangibles in the digital economy is growing rapidly in emerging and developed countries. In Russia, they have not yielded productivity gains despite the rapid upsurge of the IT industry (ISSEK HSE, 2020). Several structural features may be responsible for such a situation. Studies in the area on a company level are scarce; however, they may shed light on some reasons for the current low impact of intangibles on productivity and growth.

The current paper enlarges the extant empirical literature by revealing the role of intangibles in emerging economies. In particular, it contributes to the strand of productivity analyses and efficiency as its key component, including patterns and its development over time. It also accounts for differences in sectors due to research intensity and gives special attention to the crisis period. This may be of significant interest in the discussion on post-pandemic economic development and appropriate tools for it.

Focusing on listed companies from the manufacturing sector, the stochastic frontier model is applied to estimate the role of aggregate intangible assets as a determinant of technical efficiency. Its role as a production driver is still modest due to low investments and the level of accumulation (Shakina & Molodchik, 2014; Shakina et al., 2016; Paklina et al., 2017). Firms from high-tech sectors enjoy more extensive effects of intangibles on inefficiency decrease. After 2014, this effect was lower than before.

The consequences of the crisis were significant for all groups and widened the gap within and across the high-tech and low-tech firms. Consequently, a small subgroup of most efficient units improved its level, while others worsened their position. The dynamics of the indicator in low-tech firms reflect the increase in inefficiency due to higher dispersion.

Such disproportions have a structural nature and should be addressed with appropriate policy tools. To secure systemic investments in intangibles and digital technologies as its major component, national governments have adopted sets of measures, especially during the last years (OECD, 2019). Sectoral and time features of firms, as well as the actual endowment with intellectual capital, should be considered while designing policies.

The paper offers an analytical framework to select relevant policy tools to foster corporate investments in the development or acquisition of intangible assets. In-house research implies targeted measures, while in the case of acquisition, instruments with large business coverage are required. Both types are important to accumulate the domestic intellectual endowment and on the other hand, to adopt existing frontier technological solutions.

This approach is reasonable to consider since the share of Russian organisations engaged in technological innovation remains low. To achieve a large scale of technology adoption, small and medium companies should largely implement and use different digital solutions in technological, organisational and other domains, and restructure all business processes. Along with the problems of underinvestment in innovation, firms do not fully see the advantages of digital technologies. It is important to provide communication and financial tools to scale up domestic technologies and contribute to their dissemination across industries.

The current study has several limitations. First, due to the lack of data, only the general aggregate effects of intangibles were considered. Second, it does not account for other determinants, which are captured in the time trend. The further elaboration on these problems represents a large area for investigation in the field of productivity analysis in Russian firms.

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Evaluation of franchise system websites: the evidence from Croatia

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ABSTRACT

This paper mainly aims to provide in-depth research on how Croatian franchisors utilise the possibilities of the digital environment in terms of their digital presence. The main focus of digital presence analysis is set on franchisors' official website and supporting communication channels. For research, this paper focused on creating and testing a specialised evaluation model. The proposed model is dominantly based on three applicable models (Martinez & Gauchi, 2010; Rao & Frazer, 2005; Stefanović & Stanković, 2014) and revised according to the situational factors. A redesigned model was used to evaluate websites of Croatian franchisors, mainly focusing on the provided information, website usability, communication possibilities, and promotional activities. This research paper offers two main outcomes. The first outcome is the redesigned evaluation model, which was applied and tested with several provided improvement guidelines. The second outcome is the comparative analysis of the selected Croatian franchisors in terms of their digital presence and its relationship to several market-related indicators. The paper presents a literature review on franchising e-presence worldwide. The research results presented in this paper offer a better insight into the use of websites by Croatian franchisors. Based on their use, certain conclusions can be made. Consequently, a contribution is made to theoretical research about franchising in Croatia and can serve as a framework for further research in the region. Based on the findings of this paper and the information provided by Croatian franchisors about their products and/or services to current and potential buyers, investments in websites result in wider franchising networks and greater success in the market.

KEY WORDS

franchising, franchisor, Internet, websites, Croatia, e-commerce

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Introduction

In today's global and competitive world, customers can use opportunities created by the online presence of sellers (Shanthi & Kannainah, 2015; Reddy & Raju, 2016) and possibilities to change channels (Verhagen & Van Dolen, 2009; Madan & Yadav, 2018). In this market environment, franchisors have to choose appropriate e-commerce strategies to achieve success (Perrigot & Pénard, 2013).

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The paper mainly aims to provide in-depth research on how Croatian franchisors use the Internet for promotion and recruitment to their franchise system. The first part of the paper gives a literature review connected with the franchising business model and e-marketing. The second part presents the current franchising status in Croatia, which is the foundation of this research. The third part of the paper looks at websites of Croatian franchisors and examines them with score distribution per variable and website. Based on research results, a proposal is made on how Croatian franchisors can use their websites to expand their franchise systems. The final part presents the conclusion and proposes further research activities.

1. Literature review

1.1. Franchising

Franchising is a global business model that allows established companies to grow and expand geographically and start-up entrepreneurs to launch new ventures (Erceg, 2017). Boroian and Boroian (1987) defined that franchising occurs when a company (franchisor) licenses its brand and the way of doing business to another company (franchisee), which agrees to work following the franchising contract. Other authors defined franchising based on a different emphasis, such as trade and/or service mark (Spinelli, 2004) or a legal relationship between the parties (Emmerson, 1980) etc. The relationship between a franchisor and franchisees includes not only the product, service, and trademark, but the entire business format itself: a marketing strategy and plan, operating manuals and standards, quality control, and continuing two-way communication (Lafontaine, 1992). Companies use this business model to expand geographically without the need for extensive resources or expenditures (Alon, Alpeza & Erceg, 2010; Kavaliauskė & Vaiginienė, 2011).

Franchising offers advantages for both sides. It is a confirmed business model with market recognition ensured by the brand (Maitland, 2000) and franchisee training compensating for the potential lack of knowledge and experience (Spasić, 1996). Further benefits include the franchisor's development programme and lower risk of failure (Shane, 2005). Franchising can be used by a franchisor for expansion, i.e., to achieve faster growth with lower required capital and making use of the economies of scale. The other party, i.e., a franchisee, provides money, managers, and time (Maitland, 2000). A franchisor aiming for higher revenues from royalties faces a potential disadvantage due to the franchisee's objective to maximise earnings and control expenses (Shane, 2005). A franchise system brings franchisees advantages through location selection, standardised products and services, and lower risk of failure (Maitland, 2000; Szajt, 2013). Nieman and Barber (1987) stated that extreme control by franchisors could be a significant disadvantage for franchisees, while Selnew (1998) indicated further disadvantages, such as overdependence on the franchise system.

The franchising business model has a significant impact on the world economy. Based on Schwartzer (2016), franchising accumulates almost USD 1.6 trillion, involves more than 2.2 million companies,

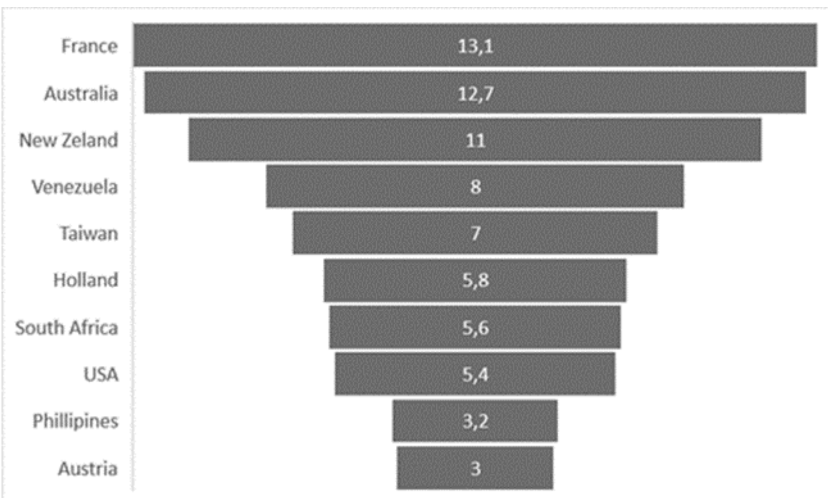

Fig. 1. Contribution of franchising to the country's GDP
Source: elaborated by the authors based on Schwartzer (2016).

employs nearly 20 million people, and its economic output comprises an important share of the national GDP averaging 4% (Fig. 1).

Franchising is gaining acceptance as a global growth strategy (Baena, 2018). According to the World Franchise Council (U.S. Commercial Service, 2018), franchising is present in all parts of the world, with China ranking first by offered franchise brands (4 500), followed by South Korea (4 288) and the USA (3 828). Chen (2019) stated that the popularity of franchising business models is still growing, giving rise to new e-business models. Thus, franchising systems must accept new technologies and adapt their operations to the growing needs of consumers and buyers.

1.2. Electronic marketing

Electronic marketing can be defined as the marketing activities of a company implemented through information and communication technologies. Many authors agree that information technologies have fundamentally changed marketing activities (Persaud & Azhar, 2012, p. 418). Numerous definitions of e-marketing have been suggested over the years. Considered as a supplement of marketing information systems, electronic marketing can be defined as the process of creation, pricing, distribution, and promotion of goods aimed at profitably satisfying customer needs and desires by using digital technologies and the Internet (Ružić et al., 2009, p. 62). According to authors, electronic marketing is the use of marketing information technologies in the process of creating, communicating, and delivering value to customers, as well as in customer relationship management, to the benefit of both the organisation and its stakeholders.

Electronic marketing campaigns are becoming more frequent and better organised, as digital platforms are ever more incorporated into marketing plans, and "electronic marketing is the opportunity of electronic communication, which is performed by the marketers, to give your support to the goods and the services towards the marketplace" (Aswathy & Vishnu, 2019, p. 7557). Consequently, electronic marketing makes it easier to define strategic target consumer groups and act faster and more flexibly adapting marketing activities to their specific needs.

The importance of electronic marketing for companies resides in "changes in the ways that today's consumers gather and assess information and make purchasing decisions, in addition to the channels they use for this process" (Leeflang et al., 2014). According to Key, "Internet has produced new efficiencies in the commoditization of information, and electronic marketing channels refer to Internet systems that can simultaneously create, promote, and deliver value from producers to consumers through digital networks" (Key, 2017). Therefore, applications for databases and technologies for contacting consumers provide electronic marketing with more detailed insight into the characteristics and behaviour of consumers. Unlike the traditional, analogue offline marketing, the most significant advantage of the digital marketing is to "be able to reach the target audience by using interactive media, and the most important difference between electronic and offline marketing is that in digital marketing the data is used properly" (Durmaz & Efendioglu, 2016).

The essential benefit of the marketing information system is the ability to monitor a company's market environment more effectively, and specifically, customer relations, to assist managers and salespeople in meeting their marketing objectives (Speier & Venkatesh, 2002, p. 98). Some authors suggest that the evolution of web technologies "has generated significant business opportunities for business organizations and their customers" (Lopez & Bonilla, 2014, p. 2). The primary component is to attract consumers and retain the best. A business that uses technologies becomes more transparent and open to the public by bringing out the research results, product specifications, encountered problems, new ideas and thoughts from partners included in the process. Furthermore, "customers additionally help businesses to improve their services while exchanging information about the services or products" (Sharafi et al., 2019, p. 120). From this viewpoint, vital technological strides are visible from the transition from web 2.0 to web 3.0 technologies and semantic search of content (Crespo et al., 2010; Lies, 2019). This approach provides additional value to products and services and can be used by businesses in electronic marketing strategies.

1.3. Franchising and e-presence

The academic research of franchising and e-presence (e-marketing, e-commerce, etc.) is still scarce. However, the importance of these topics is growing. The existing research can be divided into (i) the examination of franchisor's website contents and (ii) factors that enable the implementation of the franchisor's e-commerce website (Pénard & Perrigot, 2017).

Based on their research, Plave and Amolosch (2000) found that the franchising system usually uses one of the following four models for Internet presence (Fig. 2).

In the case of free presence, the franchisee develops a website without any restriction. In contrast, the total prohibition model forbids a franchisee from having any online presence. The second and third models provide franchisees with more or less control of their Internet presence. In the second model, the franchisor allows the franchisee to control the content of their website since the Internet is seen as a way of communication. In the third model, the franchisor develops the website and assigns sections to franchisees. Cedrola and Memmo (2009) summarised areas, in which opportunities could be created for franchising by using the Internet as (i) a tool for communication with end-users; (ii) an e-commerce tool for promotion and sales; (iii) a tool for recruitment; (iv) a tool for communication with the franchisee network; and (v) a tool for education and information used instead of or together with traditional methods.

Today, many franchisors worldwide have significant online presence using their websites, their Facebook page, a Twitter account, or other social networks (Pénard & Perrigot, 2017), and this represents the tool for communication with end-users. Franchise systems use different social networks to communicate with their customers (current and potential) to provide information about products and/or services users need or want to buy. Also, franchise systems use their websites more extensively for distribution and sales of their products and services as an addition to their physical stores.

Franchising and e-commerce have found their place in many academic disciplines, such as economics, organisational theory, marketing, and information technologies (Plave & Miller, 2001; Kremez et al., 2019b). Although the alignment of e-commerce and franchising should increase performance, these business models can be seen as fundamentally opposite. The franchising business model is seen as an effective distribution system that attracts capital by giving exclusive territorial rights to franchisees. Cliquet and Voropanova (2016) stated that e-commerce widened the geographical reach, increasing the number of customers. In franchising, one of the key benefits is a protected territory (Dixon & Quinn, 2004), which is not the case in e-commerce. Based on this, the franchise system had an initial problem accepting e-commerce in the same way as non-franchising companies (Plave & Miller, 2001). E-commerce can provide an efficient distribution method for retail and service companies (Madan & Yadav, 2018). However, many franchise systems had difficulties implementing e-commerce strategies to accommodate the needs of their clients (Kremez et al., 2019a).

Compared to other business types, franchising systems find it more complicated to coordinate different e-commerce activities and uphold the brand image. The complication arises from the need for franchisors to create an e-commerce strategy that can efficiently integrate their brand policy, marketing strategy, and distribution and maintain a good relationship with franchisees (Cedrola & Memmo, 2009). These activities must be innovative to create an optimal strategy to secure benefits from e-commerce opportunities for both parties (Chen, 2016) without any conflict with competition laws or franchise agreements (Knack & Bloodhart, 2001). Although some studies (Plave & Miller, 2001) state that e-commerce is suited for franchising due to the recognised brands and existing physical stores, others (Watson et al., 2002) underline that it could lower the need for franchising as a way of geographical expansion. According to Dixon and Quinn (2004), e-commerce will merge traditional and online retail methods. Franchising can use e-commerce for operations improvement and profitability. Combining traditional and online retail can be a challenge for franchisors. Chen (2016) noted that advice offered by Internet consultants have resulted in some conflicts between franchisors and franchisees since the consultants failed to appreciate the franchising relationship and proposed a wrong e-commerce strategy.

Lopez-Fernandez and Perrigot (2018) investigated the use of franchisee recruitment through the franchisor's websites. They examined the website content and its connection with the chain growth in terms of new potential franchisees. Their study classified information following its symbolic and functional benefit concerning the franchising system brand.

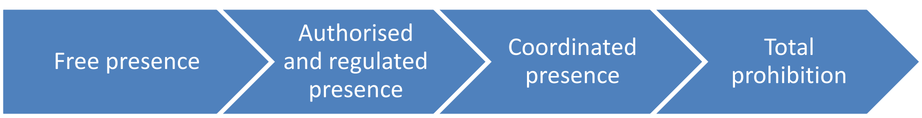

Fig. 2. Four different ways for franchising to be on the Internet, based on the franchise's level of autonomy

Source: elaborated by the authors based on Plave and Amolosch (2000).

The mentioned studies (Plave & Miller, 2001; Dixon & Quinn, 2004; Cedrola & Memmo, 2009; Cliquet & Voropanova, 2016; Frazer et al., 2016) helped to create a snapshot of e-commerce acceptance in franchising systems within different geographic situations. Still, there is a persistent need to better understand the logic behind choosing an ideal method for e-commerce implementation, especially within recognised franchise systems, which are frequently developed on the basis of traditional marketing exchange methods.

2. Franchising in Croatia

Franchising in Croatia can be divided into two phases before and after independence. The first phase started in the late 1960s with the arrival of Diners Club International to former Yugoslavia (Alon, Alpeza & Erceg, 2010). They were followed by some domestic companies like Ina (several gas stations) and Varteks (Levi's franchise) (Erceg, 2017). The arrival of McDonald's in the mid-1990s coincided with the start of the second phase of franchising in Croatia. Soon after, Croatian companies started with franchising activities, i.e., Kraš as a franchisor and Sportina and Tekstilpromet as master franchisees for fashion franchise systems (Erceg, 2018). Subway and Fornetti followed next, and shopping malls attracted other franchise systems, such as Calzedonia and Geox (Erceg & Čičić, 2013).

In Croatia, fashion and food (restaurants and fast food) are two leading industrial sectors in terms of the franchising presence (Fig. 3). They are followed by real estate agencies (Re/Max and Century 21) and foreign language schools (Helen Doron Early English) (Erceg, 2018).

According to several authors (Kukec, 2016; Erceg, 2018), 180 franchise systems are currently operating in Croatia with 17 500 employees at 1 000 different locations. Out of 180 franchise systems operating in Croatia, 25% are of Croatian origin. The biggest ones are Surf'n'fries (fast-food with more than 60 locations worldwide), Aqua (souvenir shops with 55 sites), Centar Energije (utilities with 15 locations in Croatia), and Mlinar (bakeries with more than ten locations worldwide) (Erceg, 2018). Beside traditional franchise systems in Croatia, there is one for-profit micro-franchising system Čuvar sjećanja (a burial ground management system with 10 locations in Croatia) (Erceg & Kukec, 2017).

Currently, Croatia has no legal regulation for franchising. This is not uncommon globally as only 30 countries have legally regulated franchising. In the Croatian legal system, franchising was mentioned in the Trade Act of 2003, but the term "franchising" was omitted in the amendments of 2008 (Erceg, 2016). In the remaining part of the European Union, franchising is currently defined as a vertical agreement between franchisors and franchisees partially regulated under the Vertical Block Exemption Regulation (Erceg, 2018).

Since franchising is developing as a business model in Croatia, it is also gaining importance as an academic research topic. The research about franchising can be divided into legal (Pražetina, 2005; Gorenc,

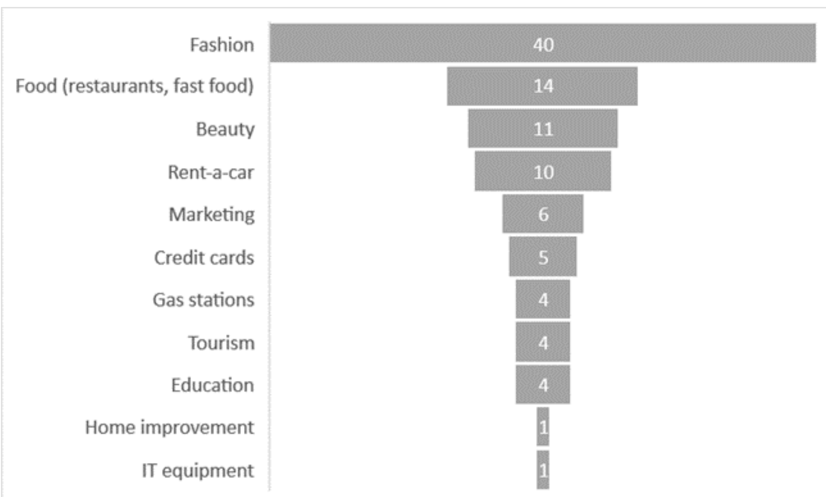

Fig. 2. Four different ways for franchising to be on the Internet, based on the franchise's level of autonomy
Source: elaborated by the authors based on Plave and Amolosch (2000).

2011) and economic parts. Under the financial topic of franchising, researchers examine franchising as a generator of development (Baresa, Ivanović & Bogdan, 2017), perceptions of different stakeholders about franchising in Croatia (Alon, Alpeza & Erceg, 2007; Alpeza, Erceg & Oberman Peterka, 2015), the importance of promotion for franchising (Buljubašić & Borić, 2014), the role of innovation in franchising (Ziolkowska & Erceg, 2016), and social franchising (Perić & Erceg, 2017).

3. Website usability and content

Usually, usability is described simply as ease of use of any given product or device. At the same time, web-usability stands for the capability of a website to be used quickly and effectively by its users (Shackel, 2009). The concept of usability in terms of website usage is fundamental when considering the significance of Internet information space and its growing adoption rate in the last two decades or more. Besides, the website content has been and still is related to website quality from several different standpoints and research goals (Rocha, 2012; Abdallah & Jaleel, 2015; Chiou, Lin & Perng, 2010). Websites are expected to provide a satisfying experience to their users (Esmeria & Seva, 2017). Furthermore, user expectations are growing at an accelerating pace. Several articles related to website usability evaluation will be briefly discussed below.

From the very beginning of the wide Internet usage in the 1990s, the idea behind web-usability gained momentum but also sparked a research interest. Jakob Nielsen is among the most influential researchers who focused on the usability topic. Nielsen is a widely cited and acclaimed author (Nielsen, 1995; Nielsen, & Loranger, 2006; Nielsen & Pernice, 2010; Nielsen et al., 2019), often referred to as "a top reference in web usability" (Martínez-Sala, Monserrat-Gauchi & Alemany-Martínez, 2020). Many studies and research efforts base their frameworks for usability testing on these principals. Furthermore, there are many different dimensions, through which the usability of websites can be evaluated (Kaur, Kaur & Kaur, 2016). However, it should be noted that the assessment of usability standards is highly time-sensitive due to the nature of everchanging user interaction with the available Internet information space.

Esmeria and Seva (2017) provided a literature review of web-usability and argued that many research studies were focusing on the design of usability. However, no standard usability index is derived to evaluate the usability of websites. Martínez-Sala, Monserrat-Gauchi and Alemany-Martínez (2020) proposed the User Usable Experience model (UUX) as a unified evaluation model that suggests a three-dimensional approach and focuses on usability, graphic design, and navigability in tourism websites. The proposed model is based on previously conducted research (Martínez-Sala, 2015). The authors found a positive correlation between the three elements and continued to confirm the value of the proposed model. Also, usability evaluation may entail the usage of analytical tools that focus on the technical aspects of websites. Kaur, Kaur and Kaur (2016) relied on automated tools to evaluate the website usability level.

4. Research methods

It should be noted that different types of websites may require different usability characteristics and goals (Esmeria & Seva, 2017). The literature review on the evaluation of franchise systems websites resulted in a somewhat limited number of relevant papers, related research efforts, and similar scientific analyses at the time of the manuscript preparation. In fact, "defining the perfect usability heuristics to evaluate certain websites is far from being a crowded area for research" (Esmeria & Seva, 2017). This research created a specialised evaluation model that focused on franchise systems websites. The proposed evaluation model is dominantly based on three applicable models: Martinez and Gauchi, 2010; Rao, 2005; Stefanović and Stanković, 2014.

Martinez and Gauchi (2010) determined the degree of website quality primarily based on website usability from the point of view of an end-user. The research was based on websites from Spanish franchises in the field of Optics and Optometry. A series of indicators based on Nielsen's usability heuristics (Nilesen, 1995) was used to measure website usability. In total, ten sets comprising 76 items were used: system status (3 items), language (3 items), user control and freedom (6 items), consistency and standards (3 items), error prevention (2 items), recognition rather than recall (3 items), flexibility and efficiency of use (6 items), minimalist design (6 items), help solving error (3 items), and help and documentation (3 items). Every item was measured on a 3-point scale (from 0 to 2).

In contrast to the previous model, which focused primarily on website usability, the other two utilised models concentrated on website content and target audience orientation. Rao and Frazer (2005) examined websites of Australian franchise systems as a communication medium for various audiences but specifically focused on franchisee prospects and potential customers. Their analytical model consists of two sets comprising 21 items: franchisee solicitation and coordination activity (11 items) and promotion activity on franchisors' websites (10 items). Every measured item used a dichotomous scale (0 and 1).

A relatively similar approach was adopted by Stefanović and Stanković (2014). They examined franchise systems in Serbia, Croatia, Australia, US, and the UK while analysing the content of franchise system websites intended for two specific audiences: franchisees and end-customers. The model uses two sets comprising 16 variables: connecting with existing and potential franchisees (9 items) and establishing a relationship with end customers (7 items). Again, every item was measured on a dichotomous scale (Yes and No).

These three models served as an initial base for the development of the revised model for the evaluation of franchise system websites. The revised model adopts both approaches, the evaluation of website usability as well as the website content, but uses adjusted measures according to the situational factors. Namely, several items used in previous models were not applicable measures due to their obsolescence.

The revised evaluation model consists of two variable sets of higher rank combining the two approaches above:

- A — Website Usability (4 constructs with 19 items),
  - A1 — Design (8),
  - A2 — Navigation (5),
  - A3 — Language (3),
  - A4 — User-control (3).
- B — Website Content (2 constructs with 15 items),
  - B1 — For franchisees (8),
  - B2 — For end-customers (7).

Every item is measured on a dichotomous scale (0 and 1). At this point in the model revision process, no additional item or construct weights were used and calculated. The total model evaluation score (Ms) per website is a sum of A (website usability score) and B (website content score). The overall score ranges from 0 to a maximum of 34, with a higher score suggesting a larger number of satisfied items, in other words, a better performing website. Due to the partially subjective nature of measured items, it is suggested that the grading of a particular item is conducted individually by several (preferably an odd number of) researchers followed by a group comparison and conclusion.

To interpret the acquired results, the mean score per item is observed. The fulfilment of the score criterion is calculated as an additional measure to estimate the level of fulfilled items against the possible maximum score ranging from 0–100%.

5. Research results

A revised model was used to evaluate a sample of 40 Croatian franchisor websites, primarily focusing on website usability and content in terms of provided information, communication possibilities, and promotional activities. A convenience sample was generated from a list of companies that belong to Croatian franchise systems having in mind the distribution in various business sectors. Every website in the sample was measured for 34 items individually by three researchers to provide an adequate level of objectivity. The items with varying scores were highlighted and discussed between researchers until the agreement has been reached for all the items. Initial scoring was conducted during September and October of 2019, as well as several sessions of discussions regarding the items with varying scores.

The research results suggest that the two best performing websites are Image Haddad (#18) and Mlinar (#24), with an identical evaluation score of Ms=26, followed by a group of 16 websites with a score of over 20 (Ms>20). This combined group of 18 websites represents the highest scoring in the data set. An additional group of 19 websites scored between 16 and 20, while the remaining three websites scored 15 and less. The suggested score margins for website grouping were created on an arbitrary basis but related to the average scores.

The distribution of research results (Table 1) suggests that websites had an acceptable outcome in the usability section (A) with a mean score of Am=14.83 (sd=1.45) out of a potential maximum of 19, meeting 78% of the potential maximum score criterion. Websites received generally good results for design

Tab. 1. Website evaluation score of selected Croatian franchisors

No.	Company name (alphabetical order)	A1	A2	A3	A4	A (sum)	B1	B2	B (sum)	Ms
1.	Aquamaritime	6	2	2	2	12	1	1	2	14
2.	BIJELI SVIJET d.o.o./LG	7	4	2	2	15	4	2	6	21
3.	Bike Express	5	3	2	2	12	2	2	4	16
4.	Business Cafe d.o.o.	8	4	1	2	15	6	1	7	22
5.	CAPACITAS CATENA j. d.o.o. (Body Creator)	8	4	2	2	16	4	3	7	23
6.	CARWIZ d.o.o.	7	4	2	2	15	4	5	9	24
7.	Cetury 21	7	4	2	3	16	5	3	8	24
8.	CHORIDIUM d.o.o. (ICE' N' GO)	6	4	2	2	14	0	1	1	15
9.	ClueGo	7	4	2	2	15	3	4	7	22
10.	Cognitum	7	4	1	2	14	2	2	4	18
11.	COMPETO d.o.o. (TORTE-I-TO)	6	4	1	2	13	1	3	4	17
12.	Diadema	8	4	2	3	17	2	5	7	24
13.	DIRECT BOOKER d.o.o. (BOOKER TOOLS)	7	4	1	3	15	5	4	9	24
14.	FMG d.o.o. (FUNNY CHIPS)	6	4	2	2	14	4	2	6	20
15.	GALEB dalmatinska trikotaža d.d.	7	4	2	2	15	3	6	9	24
16.	GRECA CENTAR d.o.o. (ČUVAR SJEĆANJA)	6	4	1	2	13	4	2	6	19
17.	Husse	8	4	1	2	15	5	4	9	24
18.	Image Haddad	8	4	1	3	16	4	6	10	26
19.	INA	8	4	2	3	17	3	4	7	24
20.	LAKA SPIKA d.o.o. (Helen Doron)	8	4	2	3	17	5	2	7	24
21.	LUMARIS STUDIO d.o.o. (TAKE ME HOME)	7	4	2	3	16	1	4	5	21
22.	Matić savjetovanje d.o.o. (WOMEN IN ADRIA)	8	4	1	2	15	0	2	2	17
23.	METAMORFOZA d.o.o. (MUZEJ ILUZIJA)	7	4	2	3	16	1	2	3	19
24.	Mlinar	8	4	2	3	17	4	5	9	26
25.	Museum of senses	8	4	2	2	16	1	3	4	20
26.	Nado Centar	7	4	2	2	15	2	3	5	20
27.	Narodne novine	7	4	1	3	15	2	5	7	22
28.	Nextbike	8	4	2	2	16	1	3	4	20
29.	PET-IT-DUO d.o.o (GOOD FOOD)	7	4	1	2	14	1	4	5	19
30.	PLACE2DESIGN d.o.o. (PLACE2GO)	8	4	2	2	16	3	3	6	22
31.	SNF ADRIA d.o.o. (SURF'N'FRIES)	7	3	1	2	13	3	1	4	17
32.	TAHOGRAF d.o.o.	6	4	1	2	13	1	3	4	17
33.	Taxi Cammeo	8	3	2	3	16	3	4	7	23
34.	Tekstilpromet	7	4	2	2	15	1	2	3	18
35.	TINKER LABS	8	4	1	2	15	3	2	5	20
36.	Tokić	8	4	2	2	16	2	2	4	20
37.	UNITAS NEKTRETNIINE d.o.o. (RE/MAX HRVATSKA)	7	4	2	2	15	3	2	5	20
38.	Vulco	6	3	1	2	12	2	2	4	16
39.	Xtravaganza	7	2	1	2	12	3	4	7	19
40.	Živa kava d.o.o. (VIVAScaffe)	7	4	1	2	14	0	1	1	15
	Descriptives	**A1**	**A2**	**A3**	**A4**	**A (sum)**	**B1**	**B2**	**B (sum)**	**Ms**
	Mean score	7.15	3.80	1.60	2.28	14.83	2.60	2.98	5.58	20.40
	Standard deviation	0.80	0.52	0.50	0.45	1.45	1.57	1.39	2.31	3.18
	Min	5	2	1	2	12	0	1	1	14
	Max	8	4	2	3	17	6	6	10	26
	Fulfilment of score criterion (%)	0..89	0..76	0..53	0..76	0.78	0.33	0.43	0.37	0.60

(A1m=7.15, sd=0.80, max=8), as well as navigation A2m=3.80, sd=0.52, max=5) and user-control (A4m=2.28, sd=0.45, max=3), while language received somewhat lower grades (A3m=1.60, sd=0.50, max=3). In contrast, the mean score for website content section (B) was considerably different, with a mean score of Bm=5.58 (sd=2.31) out of the potential maximum of 15, meeting only 37% of the potential maximum score criterion. The effect is especially apparent with content for franchisees (B1m=2.60, sd=1.57, max=8), while content for end-customers scored slightly better (B2m=2.98, sd=1.39, max=7). Simply put, website usability performed considerably better in comparison to website content, which apparently lacked expected content elements. In total, analysed websites had an average mean score of Msm=20.40 (sd=3.18, max=34), meeting 60% of the potential maximum score criterion.

6. Discussion of the results

Based on the conducted research and website analysis, several conclusions can be drawn. The observed franchise systems websites scored average results measured on the revised evaluation model scale; website usability had a considerably higher impact on the total score, while website content evaluation provided clear evidence for a significant room for improvement. These improvement possibilities are especially noticeable in the content section related to (potential) franchisees where approximately only a third of expected information was provided, on average. This issue has been detected as the biggest weakness of the observed website sample. Even though the items for measuring website usability are quite different from the website content, both aspects contribute to the website user experience and communication as well as the business goals of the given franchise system. A well-crafted franchise system website can be used as a reliable promotional tool in an integrated marketing approach (McClung et al., 2012).

Following the research results of Esmeria and Seva (2017), still, no standard usability index exists for usability evaluation, especially since different types of websites may require different evaluation approaches. Previous comparable research efforts suggest mostly similar findings. The utilisation of digital technologies and Internet-based possibilities is still at the development phase in franchise systems in Croatia (and similar markets). Websites of franchise companies are more focused on providing information to end-users than on information and services to (potential) franchisees (Stefanović & Stanković, 2014).

The proposed evaluation model offers a more comprehensive approach to understanding the franchise systems website and their heterogeneous audiences, considering the content as well as user experience thought usability standards. However, there are several noticeable limitations to its concept and usage. Website usability is significantly influenced by time-sensitive web standards, which can drastically change and evolve in relatively short periods. Besides, the model does not use any item weighing after the measurement, which could have a direct effect on the score value and interpretation. The subjective nature of utilised items in the model may result in the need for a more significant number of researchers involved in the measurement process. Further research efforts should consider these limitations and provide some solutions through rigorous model testing.

Conclusions

Irrespective of advertising techniques used by a business, the current wealth of information demands creativity and the ability to change continually. The development of technology accepted by the general population resulted in businesses minimising their activities to a small number of sites in the online environment. Businesses receive information gradually and create their strategies. The collected information may be diverse, from segmentation of users accessing the online sites to the creation of a marketing campaign dependent on the preferences and interests of users. The model evaluation aimed to analyse the websites of franchisers in the Republic of Croatia from the standpoint of information provided to end consumers (B2C) and other businesses (B2B). Although consumers use rapidly developing technologies enabling them to receive information from different sources (social networks, specialised news portals, applications, platforms, etc.), websites can still be regarded as the starting point for information due to the proximity to the primary source of information, i.e., the franchiser. From a practical point of view, the majority of the observed websites have a relatively similar architecture in terms of the design, navigation, language, and user control. However, they provide different information. Thus, this paper can help businesses as a guideline to distinguish between two levels of content they wish to distribute to businesses using their website, i.e., the information they provide to end consumers (B2C) and other businesses (B2B). From the scientific point of view, this paper expands the knowledge regarding the efficiency of websites used by franchises present in the Croatian market. Even though models (contracts) for leasing the management of the franchise, in most cases, predefine forms of promotion (including the online promotion), the research found differences in the distribution of observed variables. The research limitations are related to the rapid advancement of technologies and continually changing architecture of websites. Every user has a different subjective view of the online content. In the context of the literature review, this paper presents an overview of the most significant notions tied to electronic marketing, with an emphasis on franchises. Even though data becomes obsolete relatively quickly, the paper presented and analysed options offered by technologies in doing business. The authors attempted to track online communication methods used by Croatian franchisers and research how they used electronic marketing tools (social networks, mobile applications, etc.) together with their websites. The level of measurement brought by electronic marketing presents a strategic component of efficiency. Combined with other techniques and marketing tools, it creates prerequisites for recognisability and competitiveness in offline and online environments.

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Appendix. 1. Revised evaluation model items

Model	Construct	Items
Website Usability	Design	The logo of the brand appears in a highlighted place on the page. It uses icons and consistent images. Good use of colours and elements of design. It avoids overload of elements in the web pages. New content is emphasised. Similar elements for different actions are not used. Compatible with different browsers. Mobile friendly *sum-design (max 8)*
	Navigation	It allows the quick return to the homepage. Links are clearly recognised. Contents are well categorised. Links, website headers, and menus are clear. It provides a website map. *Sum-navigation (max 5)*
	Language	It uses clear and precise messages. It offers a choice from different languages. It offers a choice for the disabled. *Sum-language (max 3)*
	User control	The technology used is compatible with that of potential users. It offers help to avoid errors It provides a way of contacting to make suggestions or comments. *Sum-user control (max 3)*
		sum-usability (max 19)
Website Content	For franchisees	Franchisor company background Franchisor services Franchise information section Franchisees testimonials Franchisees individual website links Franchise fees and costs Qualities required of prospective franchisees The connection between franchisees and franchisor via website *sum-franchisees (max 8)*
	For end-customers	Store locations Product and service information Franchisor employment opportunities Online ordering Online payment Promotion activities (coupons, discounts, gifts) Interactive customer pages *sum-customers (max 7)*
		sum-content (max 15)
		sum-total (max 34)

Source: elaborated by the authors.

Appendix. 2. Company website addresses

NR	COMPANY NAME	WEBSITE ADDRESS
1	Aquamaritime	http://www.aquamaritime.hr/franchise_and_wholesale.php
2	BIJELI SVIJET d.o.o./LG	https://www.bijelisvijet.hr/
3	Bike Express	https://www.bike-express.hr/fransiza.html
4	Business Cafe d.o.o.	https://businesscafe.info/licences/
5	CAPACITAS CATENA j. d.o.o. (Body Creator)	https://bodycreator.com/fransize/
6	CARWIZ d.o.o.	https://www.carwiz.hr/hr/fransiza
7	Century 21	http://www.c21fransiza.hr/hr/
8	CHORIDIUM d.o.o. (ICE' N' GO)	https://icengo.eu/indexGB.html
9	ClueGo	http://www.cluego.eu/en/escape-room-franchise/
10	Cognitum	http://www.malacgenijalac.hr/
11	COMPETO d.o.o. (TORTE-I-TO)	http://torte-i-to.hr/
12	Diadema	https://diadema.hr/hr/fransize/
13	DIRECT BOOKER d.o.o. (BOOKER TOOLS)	https://www.direct-booker.com/
14	FMG d.o.o. (FUNNY CHIPS)	http://www.funnychips.eu/hr/funnychips_fransiza/default.aspx
15	GALEB dalmatinska trikotaža d.d.	http://www.galeb.hr
16	GRECA CENTAR d.o.o. (ČUVAR SJEĆANJA)	http://cuvarsjecanja.com/fransiza/
17	Husse	https://croatia.husse.com/join-our-franchise
18	Image Haddad	https://www.haddad.hr/postanite-nas-partner/
19	INA	https://www.ina.hr/
20	LAKA SPIKA d.o.o. (Helen Doron)	https://helendoron.hr/postanite-fransizer/
21	LUMARIS STUDIO d.o.o. (TAKE ME HOME)	https://takemehome.hr/
22	Matić savjetovanje d.o.o. (WOMEN IN ADRIA)	https://www.womeninadria.com/
23	METAMORFOZA d.o.o. (MUZEJ ILUZIJA)	https://muzejiluzija.com/
24	Mlinar	https://www.mlinar.hr/en/poslovanje
25	Museum of senses	https://museumofsenses.com/
26	Nado Centar	http://www.nado.hr/fransiza/
27	Narodne novine	https://www.nn.hr/hr/komercijala/ustroj/
28	Nextbike	http://www.nextbike.hr
29	PET-IT-DUO d.o.o (GOOD FOOD)	https://goodfood.hr/
30	PLACE2DESIGN d.o.o. (PLACE2GO)	http://place2go.hr/fransize/
31	SNF ADRIA d.o.o. (SURF'N'FRIES)	http://surfnfries.com/
32	TAHOGRAF d.o.o.	http://www.tahograf.hr
33	Taxi Cammeo	https://cammeo.hr/hr
34	Tekstilpromet	https://www.tekstilpromet.hr/brand/o-maloprodaji/
35	TINKER LABS	https://tinkerlabs.hr/fransiza/
36	Tokić	http://www.tokic.hr/onama/
37	UNITAS NEKTRETNIINE d.o.o. (RE/MAX HRVATSKA)	https://www.remax.hr/_/Croatia?Lang=hr-HR
38	Vulco	https://www.vulco.hr/hr/o-nama
39	Xtravaganza	http://www.xtravaganza.hr/o-xtravaganzi/
40	Živa kava d.o.o. (VIVAScaffe)	https://vivasbar.hr/

Source: elaborated by the authors.

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Network capability, relational capability and Indonesian manufacturing SME performance: an empirical analysis of the mediating role of product innovation

Naili Farida Nuryakin

ABSTRACT

The relational capability can create networks and build relationships to be an essential part of a company to improve business performance. This study aims to empirically prove the influence of knowledge sharing on product innovation, the effect of network capability on product innovation and business performance, the effect of relational ability on product innovation and business performance, and the effect of product innovation on business performance. The sample of this research was created from owners of batik manufacturing SMEs in Lasem, Rembang, Central Java. The study used SEM-PLS for analysis. The results found that (1) knowledge sharing had a positive and significant effect on product innovation; (2) network capability had a positive and significant impact on product innovation and business performance; (3) relational ability had a positive and significant effect on product innovation and business performance; (4) greater effect of product innovation affects business performance. The role of product innovation is to mediate between knowledge sharing and marketing performance. SMEs can improve business performance.

KEY WORDS

knowledge sharing, network capability, relational capability, product innovation, business performance

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Introduction

Knowledge is the key to the success of an organisation (Kim & Lee, 2013) and is one source of competitive advantage in dealing with an uncertain environment (Zhang & Jiang, 2015). One part of knowledge management is knowledge sharing. The pace of innovation cannot be confronted with the traditional approach of resource allocation; therefore, companies have to seek new business models to favour advances of embedding upgraded technology

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for their products and services. In this respect, knowledge sharing and open innovation become crucial in confronting uncertainty with competition reaction and growing client expectations. The study by Yeşil, Koska, and Buyukbese (2013) explained the importance of the knowledge sharing process in achieving innovation capability. Therefore, knowledge sharing and innovation are two important and interrelated subjects that need to be further explored to understand their dynamics and implications for an organisation.

Knowledge sharing activities are among the competitive advantages that companies must possess (Abdul-Jalal, Toulson & Tweed, 2013; Cabrera, Collins & Salgado, 2006; Nonaka, 1991; Spender & Grant, 1996; Nwaiwu et al., 2020; Usman, Hartani & Sroka, 2020). Sharing information will help employees of different divisions understand various definitions. Information can also be shared between companies and even competitors. Information sharing impacts business innovation and performance (Rao, Guo & Chen, 2015).

The ability to create networks and build relationships becomes an essential part of an organisation. The role and importance of inter-organisational relationships in competitive advantage and company performance have received increasing attention over the last two decades (Ngugi & Johnsen, 2010). The ability of companies to build networks affects their ability to access scarce resources needed to pursue opportunities (Aldrich & Carter, 2004). This capability enables them to exploit and mobilise complementary network resources from their interaction partners (i.e., resources that they do not have) and create value despite resource constraints (Mu, 2013). This makes the company more innovative (Wang & Wang, 2012) and ensures high performance (Ranjay Gulati, 1999; Hoffman, 2007).

According to Eshlaghy and Maatofi (2011), innovation is crucial for enhancing performance. Eris and Ozmen (2012) found that innovation affects performance. However, other studies explain that innovation does not support marketing performance (Mavondo, Chimhanzi & Stewart, 2005). Salavou and Avlonitis (2008) found that product innovation activities, innovation and concept innovation did not have a significant impact on company performance. Based on the two differences in the results of the study, a research gap remains in examining the importance of the role of innovation in improving company performance, which requires further research.

This research was conducted on a sample of batik SMEs in Lasem, Rembang, Central Java. The empirical investigation targeted the relationship between knowledge sharing on product innovation, network capability on product innovation and business performance, relational ability on product innovation and business performance, and product innovation on business performance.

This study aimed to empirically prove and test the effect of knowledge sharing on product innovation, test the impact of network capability on product innovation and business performance, examine the impact of relational capacity on product innovation and business performance, and test the impact of product innovation on business performance. The study also contributed to closing the research gap and discussed the effect of innovation on performance.

1. Literature review

1.1. Knowledge sharing

The basic principle established in the field of knowledge management is the fact that knowledge can be shared (Nonaka & Takeuchi, 1995). Knowledge sharing refers to providing information and knowledge to help others. In the context of collaboration, knowledge sharing is useful for solving problems, developing new ideas, or implementing policies or procedures (Cummings, 2004).

Van den Hooff and De Ridder (2004) defined knowledge sharing as the process by which individuals exchange knowledge and create new knowledge together. Ardichvili, Page and Wentling (2003) explained that in knowledge sharing, one party must share knowledge, and another must receive it. Within an organisation, one way to share knowledge is to share work experience, expertise, knowledge, and contextual information between employees (Lin, 2007).

Knowledge-sharing activities can impact other business processes. Information and knowledge significantly affect the quality of managerial decision making (Raghunathan, 1999). Companies that engage in knowledge-sharing activities impact innovation (Lin, 2007; Marina du, 2007) and business performance (Matin, Alvani, Jandaghi & Pashazadeh, 2010; Rao et al., 2015; Saraf, Langdon & Gosain, 2007; Surijah, 2015).

1.2. Network capability

There are various definitions of network capability. It is perceived as the company's ability to initiate, develop, and utilise internal organisational and external organisational relationships (Zacca, Mumin & Ahrens, 2015). The basic concept is that companies can build, manage, and exploit relationships (Ritter & Gemunden, 2003). Lambe, Spekman, and Hunt (2002) and networking capabilities, such as the ability to find, build and manage relationships. Companies must develop close relationships with external parties (Mascarenhas, Bajeva & Jamil, 1998). Thornton, Henneberg, and Naude (2014) proposed the concept of organisational networking as corporate behaviour, namely activities/routines/practices, which enable an organisation to understand and utilise its network of business relationships, both direct and indirect.

Companies that can create high-quality relationship will achieve performance (Nuryakin & Retnawati, 2016). Network capability can help discover other skills within the organisation (Vesalainen & Hakala, 2014). High-quality business networks enable companies to identify opportunities, access the wealth of information, and undertake effective and efficient knowledge transfers and resource mobilisation (Achrol & Kotler, 1999; Uzzi, 1996). Companies that have secure business networks also have a better understanding of their environment (Henneberg, Naude & Mouzas, 2010). Network capability is also a source of competitive advantage for companies (Mitrega et al., 2012). Acquaah (2012) showed how companies with secure networks influenced business performance.

1.3. Relational capability

The key to a company's success lies not only in internal but also in external resources. External resources originate outside the company and arise from the fabric of relationships established between the company and external parties. Market-based relational resources are among the essential capabilities that a company must have to increase competitive advantage and performance (Nuryakin & Ardyan, 2018a). Relationships developed with external parties, such as customers and strategic partners, have also proven to be essential sources of knowledge and abilities (Kale, Singh & Perlmutter, 2000) and have the potential to increase innovation. As a result, companies depend on the quality and quantity of their relationship (Powell, 1996). Smirnova, Naude, Henneberg, Mouzas, and Kouchtch (2011) argued that the definition of relational capability has two approaches, namely, (1) relational capacity is the acceleration of access to knowledge, support, innovation, and the creation of competitive advantage; and (2) the company's ability to communicate, coordinate, and regulate business interactions.

1.4. Product innovation

Company leaders must prioritise innovation (Leavy, 2005), e.g., by focusing on research and development. R&D is the driver for a variety of products or services. The focus on innovation positively impacts competitive advantage (Nuryakin, 2018). Innovation also affects company success (Christian, 1963) and performance (Ardyan, 2016).

New products have different levels of innovation. Boer and During (2001) defined innovation as the process of creating new products, new markets, new technologies, new organisations, or a combination of these. Innovation activities must result in something new to the target audience to attract customers (Husein & Nuryakin, 2018). Various studies on the innovation levels explain multiple types, such as radical, incremental and moderate innovation or genuinely new products (Garcia & Calantone, 2002; Herrmann, Gassmann & Eisert, 2007; Janssen, Stoopendaal & Putters, 2015; Souto, 2015; Un, 2010; Utterback & Abernathy, 1975). Radical innovations tend to occur on a large scale and incremental on a small scale. Moderate innovations are linked to the existing scale of innovation. New products mean novelty in terms of the outcome and processes used for production.

1.5. Business performance

Performance is one indicator that explains how a business is doing. The measurement of business performance is somewhat diverse. Jaworski dan Kohli (1993) described indicators of business performance as market share, organisational commitment, esprit de corps, and overall performance. Slater and Narver (1994) considered ROA, sales growth, new product success as business performance. Matear, Osborn, Garrett, and Gray (2002) divided business performance into two types, namely, market and financial performance. Wang, Hult, Ketchen, and Ahmed (2009) looked at business performance as subjective and objective performance.

According to Sin, Tse, Chan, Heung, and Yim (2006), performance can be achieved by comparing a business to its main competitors based on seven aspects, comprising (1) sales growth; (2) customer retention; (3) return on investment (ROI); (4) stocks on the market; (5) trust; (6) consumer satisfaction;

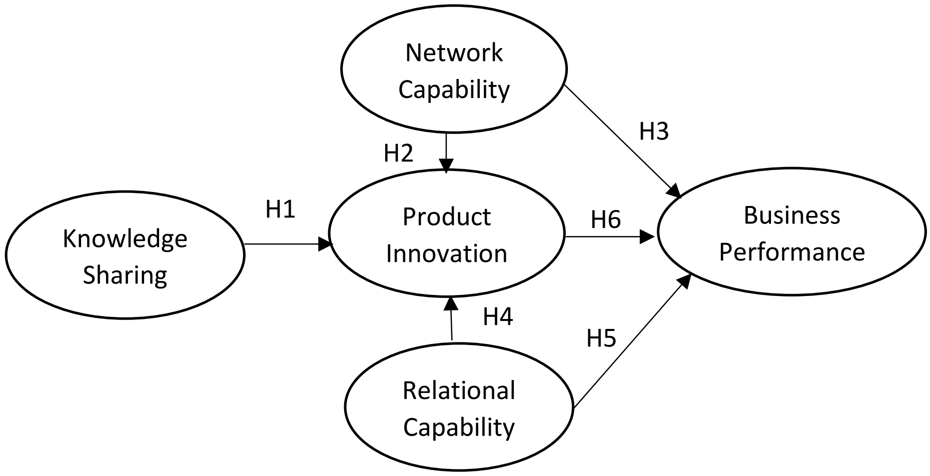

Fig. 1. Empirical research model

and (7) return on sales (ROS). Meanwhile, Sharabati, Jawad, and Bontis (2010) measured business performance using dimensions of productivity, profitability, and market valuation. Najib and Kiminami (2011) measured the dimensions of marketing performance with three indicators: sales volume, profitability, and market share. Nuryakin and Ardyan (2018b) focused on evaluating marketing performance in international markets, looking at sales growth, increasing product offering, product value, and market coverage.

Based on the literature review, the empirical research model was developed for this study (Fig. 1).

2. Hypothesis Development

2.1. Impact of knowledge sharing on product innovation

Alawi, Kayworth, and Leidner (2005) argue that knowledge can spread, be implemented, and developed through knowledge sharing. Knowledge sharing can motivate individuals to think more critically and more creatively so that they can eventually produce new knowledge. Companies can profit from such knowledge in various ways. Jantunen (2005) argued that an organisation that shared and gathered knowledge could enjoy superior innovation capabilities. Lin (2007) explained that gathering and donating knowledge are two strictly necessary concepts that influence a company's innovation capability. The study by Yeşil et al. (2013) confirmed a hypothesis that the knowledge sharing process influenced the innovation capability of firms.

Based on theoretical and other previous studies, the following hypothesis was developed:

H1: Knowledge sharing has a positive and significant effect on product innovation.

2.2. Impact of network Capability on Product innovation

Companies try to build relationships with other companies in a network to get access to the needed assets (Kogut & Zander, 1992; Pfeffer & Salancik, 1978). The assets can be in the form of tools, capabilities, resources etc. Merging these assets is likely to affect the creativity of the company. Creativity can influence the improvement of innovation within the company. Building a network means having better access to information and, thus, being in a stronger position to influence and benefit from network activities (Chiu, 2009), where one of the benefits is generating creative ideas. Building links or networks with surrounding partners allows companies to get more information from the environment, which is an essential element for the success of innovation (Astley & Sachdeva, 1984; Ritter & Gemunden, 2003). Based on theoretical and other previous studies, the following hypothesis was developed:

H2: Network capability has a positive and significant effect on product innovation.

2.3. Impact of network capability on business performance

Companies must make connections through networks in an attempt to access resources and capabilities (Ranjay Gulati, Nohria & Zaheer, 2000). The accessed resources and capabilities can affect company performance (Ranjay Gulati, 1999; Hoffman, 2007). Companies that have extensive networks find it easier to market their products. It is expected that a more extensive network can increase the company's market share and sales.

Based on theoretical studies and other previous studies, the following hypothesis was developed:
H3: Network capability has a positive and significant effect on business performance.

2.4. Impact of relational capability on product innovation

Swan et al. (2007) discussed the importance to integrate relational skills related to innovation in the health sector. Based on the analysis of this study, relational capabilities are essential in developing innovation. A study conducted by Ngugi and Johnsen (2010) concluded that relational skills were crucial for a company faced with changing relationship needs and responding to market challenges. Innovation possibilities can be increased by supplier collaboration with customers. The advantage of this collaboration manifests through co-creation value that boosts innovation. Other studies conducted by Oshri, Kotlarsky, and Gerbasi (2015) showed that the relationship established between producers and suppliers had a significant impact on improving strategic innovation.

Based on theoretical and other previous studies, the following hypothesis was developed:
H4: Relational capability has a positive and significant effect on product innovation.

2.5. Impact of relational capability on business performance

Sin, Tse, Yau, Chow, and Lee (2005) showed that the impact of relationship marketing orientation in each country is different. The impact of relationship marketing orientation in a capitalist country (Hongkong) is less effective than in countries whose economies are centrally managed by the government (mainland China). Therefore, managers (companies that expand to various countries) must pay attention to ethnocentrism to understand the different market environments. A company must pay attention to the level of uncertainty (in terms of environment, technologies, legislation, commitment, price, and local culture) to determine whether to use relationship or transactional marketing. This decision will affect the company's performance (Abramson & Ai, 1998). Based on a study conducted by Luo, Griffith, Liu, and Shi (2004), the influence of customer relations on financial performance is greater than the social capital of business partners and government social capital.

Based on theoretical and other previous studies, the following hypothesis was developed:
H5: Relational capability has a positive and significant effect on business performance.

2.6. Impact of innovation on business performance

Innovation is one of the competitive advantages of a company, and can be a significant enabler in the creation of value and maintenance of competitive advantage in an increasingly complex and rapidly changing environment (Subramaniam, 2005). In general, innovation can fully use the existing resources, increase efficiency and potential value as well as bring new intangible assets to the organisation. Companies with more significant innovation efforts will be more successful in responding to customer needs and developing new capabilities that enable them to achieve better performance or superior profitability (Calantone, Cavusgil & Zahao, 2002). Successful innovation activities undoubtedly have a positive impact on performance (Ardyan, 2016).

Based on theoretical and other previous studies, the following hypothesis was developed:
H6: Product innovation has a positive and significant effect on business performance.

3. Empirical testing model and methodology

3.1. Research samples

This research focused on batik manufacturing SMEs in Lasem, Central Java, Indonesia. The study used purposive sampling as the sampling technique. The sample of batik manufacturing SMEs in Lasem had to correspond to the following criteria: the study respondents had to be owners of a batik manufacturing SME in Lasem; and the number of employees working at batik manufacturing SMEs in Lasem had to be at least five people. To obtain data, the researchers distributed questionnaires to 150 batik manufacturing SMEs in Lasem, Indonesia. One hundred questionnaires fully completed and eligible for analysis. So, the research sample amounted to 100 owners of batik manufacturing SMEs in Lasem.

In the research sample, 33% of respondents were male, and 67% were female, 60% were more than 40 years old, and the remaining 40% were 30–40. Most respondents graduated from a high school (47%), followed by junior high school (42%) and elementary school (47%). Almost all respondents (99%) were married, and one was single. The highest income earned by respondents was between Rp. 6–7 million (38%). Other characteristics were the company age and the number of employees. Most companies were 4–5 years of age (38%), and the highest number of employees was between 10–50 (64%). Respondent characteristics are detailed in Table 1.

4. Analysis

The researchers used SEM-PLS to analyse the study data and WarlpPLS version 5.0 to process it. SEM-PLS was chosen because (1) the sample was relatively small, i.e., 100 batik SME owners/managers; and (2) it does not consider data normality.

Tab. 1. Respondent characteristics

Respondent characteristics	Frequency	Percentage
Sex		
Male	33	33%
Female	67	67%
Age		
<30 years old	0	0%
30–40 years old	40	40%
>40 years old	60	60%
Education		
Elementary school	11	11%
Junior high school	42	42%
Senior high school	47	47%
Marital status		
Married	99	99%
Unmarried	1	1%
Company age		
< 1 year	0	0%
2–3 years	1	1%
4–5 years	43	43%
More than 5 years	39	39%
Income		
<Rp. 5 million	4	4%
Rp. 6–10 million	38	38%
Rp. 11–15 million	21	21%
Rp. 15 million	37	37%
Number of		
employees	31	31%
<10	64	64%
10– 50	5	5%
>50		

5. Measurement

The instruments used in this study were based on a 5-point Likert scale, where 1 meant "strongly disagree" and 5 — "strongly agree". The following indicators were used for each research variable:

- Knowledge sharing. SME owners can develop knowledge from customers and assimilate information about customers. SME owners can disseminate information to customers and align their knowledge with customer value.
- Network capability. SME owners can coordinate discussions with customers and partners. They have skills in dealing personally with customers and partners and have partners sharing knowledge with customers and partners. They also have internal communication with customers and partners (Zacca et al., 2015)
- Relational capability. SME owners are able and skilled at interacting with profitable customers, capable and competent at obtaining valuable customers, competent and qualified at retaining useful customers. They have customer trust and committed relationships with clients.
- Product innovation. SME owners carry out activities related to the development of new products using different raw materials. They improve product quality and attributes and use different models to develop products.
- Business performance. SME owners can obtain increased revenue, achieve sales targets, and gain increased profits.

6. Result

6.1. Reliability and validity

The reliability test used composite reliability and Cronbach's alpha. To confirm the reliability, the composite reliability and Cronbach's alpha values had to be greater than 0.60. The composite reliability and Cronbach's alpha values are given in Table 1. In this study, composite values of variables were 0.874 (knowledge sharing), 0.878 (network capability), 0.911 (relational capability), 0.899 (product innovation), and 0.922 (business performance). The Cronbach's Alpha values were 0.806 (knowledge sharing), 0.814 (network capability), 0.876 (relational capability), 0.858 (product innovation), and 0.873 (business performance). Therefore, the instruments developed in this study were considered as reliable as the value of composite reliability, and Cronbach's alpha was greater than 0.60.

The validity test used convergent validity (loading factor and Average Variance Extracted (AVE)) and discriminant validity (comparing AVE roots with correlations between variables). The loading and AVE factor values had to be above 0.5 (Ghozali, 2013). Table 2 shows that all loading factor values and AVE values were above 0.5. Discriminant validity was compared between the square root of AVE and the correlation between variables. Table 3 shows the square root AVE> relationship between variables, so both loading factors, AVE and discriminant validity indicated that the instruments developed in this study were valid.

Tab. 2. Reliability and validity test results

	Factor loading	AVE	Cronbach's Alpha	Composite reliability
Knowledge sharing KS1 KS2 KS3 KS4 KS5	 0.790 0.812 0.803 0.873 0.729	0.636	0.806	0.874
Network capability NC1 NC2 NC3 NC4	 0.734 0.763 0.855 0.852	0.644	0.814	0.878
Relational capability RC1 RC2 RC3 RC4 RC5	 0.881 0.875 0.839 0.791 0.701	0.672	0.876	0.911
Product innovation INN1 INN2 INN3 INN4 INN5	 0.777 0.812 0.803 0.873 0.729	0.640	0.858	0.899
Business performance BP1 BP2 BP3	 0.909 0.865 0.904	0.797	0.873	0.922

6.2. Goodness of fit

Model fit explains whether data support the proposed model. All goodness of fit indicators demonstrated that the built model fit with the research data. The following indicators were used in this study:

- Average path coefficient (APC)=0.279, P<0.001
- Average R-squared (ARS)=0.569, P<0.001
- Average adjusted R-squared (AARS)=0.555, P<0.001
- Average block VIF (AVIF)=2.160, acceptable if < 5, ideally < 3.3
- Average full collinearity VIF (AFVIF)=2.396, acceptable if < 5, ideally < 3.3
- Tenenhaus GoF (GoF)=0.621, small > 0.1, medium > 0.25, large > 0.36
- Simpson's paradox ratio (SPR)=1.000, acceptable if > 0.7, ideally = 1
- R-squared contribution ratio (RSCR)=1.000, acceptable if > 0.9, ideally = 1
- Statistical suppression ratio (SSR)=1.000, acceptable if >0.7
- Nonlinear bivariate causality direction ratio (NLBCDR)=1.000, acceptable if > 0.7

7. Hypothesis test

Hypothesis 1 states that knowledge sharing has a positive and significant effect on product innovation. The results of this study indicated that knowledge sharing has a positive and significant effect on product innovation (β = 0.247; p = 0.005). So, H1 is accepted.

Tab. 3. Discriminant validity

	Relational capability	Knowledge sharing	Product innovation	Network capability	Business performance
Relational capability	**(0.820)**	0.681	0.734	0.644	0.695
Knowledge sharing	0.681	**(0.798)**	0.652	0.577	0.515
Product innovation	0.734	0.652	**(0.800)**	0.601	0.563
Network capability	0.644	0.577	0.601	**(0.803)**	0.578
Business performance	0.695	0.515	0.563	0.578	**(0.893)**

Tab. 4. Hypothesis test results

Hypothesis	Result*	Explanation
H1: Knowledge sharing → Product Innovation	β= 0.247; p= 0.005	Hypothesis accepted
H2: Network capability → Product Innovation	β= 0.202; p= 0.018	Hypothesis accepted
H3: Network capability → Business Performance	β= 0.232; p= 0.008	Hypothesis accepted
H4: Relational capability → Product Innovation	β= 0.433; p< 0.001	Hypothesis accepted
H5: Relational capability → Business Performance	β= 0.520; p< 0.001	Hypothesis accepted
H6: Product innovation → Business Performance	β= 0.040; p= 0.342	Hypothesis rejected

*$\alpha < 0.05$

Hypothesis 2 maintains that network capability has a positive and significant effect on product innovation. The results of this study indicated that network capability has a positive and significant effect on product innovation ($\beta = 0.202$; $p = 0.018$). So, H2 is accepted.

Hypothesis 3 says that network capability has a positive and significant effect on business performance. The results of this study indicated that network capability has a positive and significant effect on business performance ($\beta = 0.232$; $p = 0.008$). So, H3 is accepted.

Hypothesis 4 states that relational capability has a positive and significant effect on product innovation. The results of this study indicated that relational capability has a positive and significant effect on product innovation ($\beta = 0.433$; $p < 0.001$). So, H4 is accepted.

Hypothesis 5 says that relational capability has a positive and significant effect on business performance. The results of this study indicated that relational capability has a positive and significant effect on business performance. So, H5 is accepted.

Hypothesis 6 maintains that product innovation has a positive and significant effect on business performance. The results of this study indicated that product innovation has no significant impact on business performance. So, H6 is rejected.

8. Discussion

8.1. Relationship between knowledge sharing and product innovation

The results of this study indicate that product innovation will affect business performance more. Besides, knowledge sharing has a positive and significant effect on product innovation.

These research results support previous studies stating that knowledge sharing activities can increase innovation (Jantunen, 2005; Lin, 2007). A company's ability to transform and exploit knowledge can determine the level of innovation (Wang & Wang, 2012), such as new problem-solving methods and new products for rapid reaction to market demand (Marina du, 2007; Tidd, Bessant & Pavitt, 2005). Jantunen (2005) argued that contributing and gathering knowledge in organisations can lead to superior company innovation capabilities.

The results of this study indicate that network capability can improve product innovation and business performance. These results are in line with previous studies stating that network capability can promote product innovation (Astley & Sachdeva, 1984; Chiu, 2009; Ritter & Gemunden, 2003) and business performance (Ranjay Gulati, 1999; Hoffman, 2007). Network partners are critical in helping companies realise their strategic goals and are recognised for their role in helping innovation activities and company growth (Ahuja, 2000). Previous research showed that most technology-based companies depended on their networks to succeed and would find it challenging to innovate, or even survive, outside the network (Powell, Koput & Smith-Doerr, 1996; Tang, Mu & Maclachlan, 2008; Yaprak, Cavusgil & Kandemir, 2006). In the batik industry in Lasem, networking capabilities enable companies to improve product innovation and business performance.

The study results indicate that relational capability can improve product innovation and business performance. These results are in line with previous studies, maintaining that relational capability can improve product innovation (Ngugi & Johnsen, 2010; Oshri et al., 2015) and business performance (Abramson & Ai, 1998; Luo, Griffin, Liu & Shi, 2004). In relationships between parties, trust is required (Morgan & Hunt, 1994). Trust in suppliers, co-workers, clients, governments, and other business units contributes to innovation (Tsai & Ghoshal, 1998). The company's ability to establish relationships makes each party willing to share information. Customers are eager to share information and technology know-how with their suppliers. Suppliers can understand customer needs and problems better, which is the basis for increasing customer satisfaction (Narver & Slater, 1990). Customer satisfaction can increase their loyalty to continue buying products (Boonlert-vanich, 2011; Chang & Tu, 2005). Satisfaction and loyalty become part of business performance.

The study results indicated that product innovation could not significantly improve business performance. This result differed from previous research, which stated that innovation had a positive and significant effect on business performance (Ardyan, 2016; Calantone et al., 2002). There are reasons why product innovation cannot significantly improve business performance. The batik industry, especially in the Lasem area, has a form and pattern of motifs that are difficult to change radically. The focus of innovation for batik SMEs in Lasem is likely to tend to incremental innovation. The lack of the focus of research variables on incremental innovation is the cause of the insignificant influence of innovation and business performance.

The results of this study indicate that the product innovation carried out by batik SMEs in Lasem does not increase sales performance. The basis of product innovation carried out at batik SMEs in Lasem is product orders from customers, who generally have their own motives or designs in ordering products.

Conclusions

The conclusions in this study are as follow: first, to improve product innovation, a company must do three essential things, namely, (1) conduct knowledge transfer activities, (2) have network capabilities, and (3) build relational capabilities. Second, business performance improvement requires the ability to build networks and establish relationships. Third, product innovation does not improve business performance.

This study indicated and contributed to the closing of the research gap. Also, it debated the mediating role of innovation in business performance. Based on the study, empirical research also explained that product innovation does not significantly improve business performance. This study supports previous research that explained the failure of innovation to support performance (Mavondo et al., 2005). This research also supports the results of the study by Salavou and Avlonitis (2008), who claimed that product innovation had no significant impact on company performance.

The managerial implication in this research is that companies must improve to create secure networks and relationships with stakeholders. Building a strong network and having good relationships with business partners will make companies share knowledge, skills, technologies, and resources. Consequently, companies will develop product innovation more easily and will have a positive impact on business performance.

There are several limitations to this study: (1) the sample used is small, (2) it does consider cultural aspects in the batik industry, and (3) it does not consider data normality. Therefore, future research should (1) enlarge the sample, (2) consider cultural aspects in their effects on business performance, and (3) use covariate-based SEM to find the assumption of data normality.

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Ensuring economic efficiency of flexible fixtures in multiproduct manufacturing

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ABSTRACT

The first-priority directions for modern engineering, especially for multiproduct manufacturing, include the intensification of manufacturing processes, increasing the efficiency of technological equipment, and reducing the time required to implement technological solutions. Fixture design is a complicated and time-consuming process that requires considering many parameters of the closed-loop technological system "machine tool — fixture — cutting tool — workpiece". One machined part can have several fixture layouts corresponding to all specified parameters; however, their effectiveness differs depending on production conditions. Search for an optimal fixture for specified production conditions is an essential stage of production planning. It has been proved that the efficiency of a manufacturing process should be assessed using single economic indicator — the cost of machining, which considers the costs of time, the total costs for process realisation, and a batch of parts. The paper aims to substantiate the efficiency of manufacturing processes in machining complex parts using flexible fixtures by developing a mathematical model that considers the cost of time, the cost of implementing the manufacturing process, and the batch value of parts production. This approach estimates the efficiency of manufacturing processes for machining complex parts and choosing the flexible fixture layout that corresponds to specific production conditions. It was proved that flexible fixtures could be effectively used for machining small batches of parts with frequent readjustments to new workpieces and short-term machining. A tendency has been established that the higher number of nomenclature of parts contributes to expanding the scope of the effective use of flexible fixtures.

KEY WORDS
flexible manufacturing, fixture design, multiaxis machining, cost of machining

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Introduction

In modern engineering, the main challenge is to reduce the time spent on the design and manufacture of products, which is continually becoming more complicated, since increasingly more varieties of similar products are needed in today's market. Ivanov et al. (2019) noted that the range of engineering products had increased by 2.5 times, and it is also important to note the growing complexity as well as requirements for accuracy and quality. Therefore,

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metalworking equipment and processes must become more flexible to ensure the competitiveness of products and the response to market needs as well as to reduce market entry time. This necessitates to develop and implement fundamentally new design and technological solutions for using automated technological equipment as multiaxis machining centres to locate, clamp, and orient workpieces in the machining area, ensuring high-quality products. The first-priority directions in the development of modern manufacturing engineering technologies, especially multiproduct manufacturing, include intensified manufacturing processes and increased efficiency of technological equipment. Given the increase in the range of engineering products, flexible fixtures form the basis for ensuring high product quality, increasing productivity, and reducing the complexity of manufacturing processes.

The efficiency of implemented fixtures depends on several factors, the most important of which is the range of machined parts. The minimum batch size of parts is limited by specific costs for developing and debugging fixtures. As the batch size increases, the unit costs decrease, which contributes to the efficiency of fixtures.

The investigation into modern experience has shown that many research efforts are devoted to efficiently functioning manufacturing systems, but no single approach considers all these factors.

Therefore, this paper aims to substantiate the efficiency of manufacturing processes for machining complex parts using flexible fixtures by developing a mathematical model that considers the cost of time, the cost of implementing the manufacturing process, and the batch size. Research objectives include:

- the analysis of modern approaches to the effectiveness of flexible fixtures in multiproduct manufacturing;
- the development of a mathematical model that substantiates the efficiency of manufacturing processes for machining complex parts using flexible fixtures based on comparative economic efficiency and considering the cost for implementing the manufacturing process and the batch size;
- piloting the practical implementation of the proposed mathematical model using batches of differently configurated forks.

The paper contains a literature review with the identified research problem and recent research results by other scientists, the research methodology with the proposed scientific approach, results with calculated data for different production conditions, the discussion substantiating achieved scientific novelty and recommendations for practical implementation, and, finally, conclusions that summarise the main results of research.

1. Literature review

The manufacture of engineering products saw the increase in the share of the CNC multiaxis machining centres aimed at intensification and automation of production, which can be significantly restrained by structurally obsolete (inflexible) fixtures that require much more auxiliary time for changing coordinates of the machined surfaces. This can be corroborated by the fact that under current typical conditions of rapid development and use of the latest technologies, the engineering industry is constantly introducing new and more efficient manufacturing processes and equipment for implementation at enterprises around the world.

As confirmed by the following data, fixtures play one of the most significant roles in engineering product manufacturing. According to Kotliar et al. (2019), the share of fixtures in the total amount of tooling is 70–80%. Hashemi, Shaharoun and Sudin (2014) proved that the production costs for the design and manufacture of fixtures could reach 90%. Bi and Zhang (2001) reported that costs of fixtures comprise 10–20% of the total costs of manufacturing systems. Nixon (1971) maintained that up to 40% of defective parts in machining might have occurred due to imperfections of fixtures. Rong and Zhu (1999) stated that approx. 70% of new designs of fixtures were a modification of existing ones.

The development of modern, efficiently functioning manufacturing systems requires careful production planning. To date, world engineering is dominated by multiproduct manufacturing, which is characterised by a wide range of products, the reduction of unproductive time, the introduction of highly efficient CNC multiaxis machining centres, and the decrease in the number of technological equipment units. Ivanov et al. (2019) demonstrated the need to develop and implement fixtures, providing multiaxis machining of parts with sufficient tool availability.

The design of flexible fixtures is a complicated and time-consuming process that requires considering many parameters. Kotliar et al. (2019b) focused on production conditions; Krol and Sokolov (2018) considered technological capabilities of metal-cutting equipment; Li, Chen and Shi (2016), Kostyuk, Nechyporuk and Kostyk (2019), and Kostyuk (2019) examined parameters of cutting tools; Bakker et al. (2013) and Shaik, Rao and Rao (2015) studied design and technological features of parts; Basova et al. (2018) and Sokolov, Krol and Baturin (2019) investigated dynamic characteristics; Denysenko et al. (2019) and Dynnyk et al. (2020) evaluated quality indicators; and Yarovyi and Yarova (2020) appraised energy-efficient criteria. Meanwhile, Qin et al. (2010) presented a literature review on existing fixture systems, their functionality, design features, and sufficient use.

Ansaloni et al. (2013) and Matteo et al. (2013) noted that when designing the manufacturing process of machining parts for the automotive industry with CNC machines, it is crucial to strive to intensify machining processes, increase the flexibility of equipment and processes, and productivity levels. Son and Park (1987) stated that productivity, quality, and flexibility were key indicators of production efficiency integrated into the model for evaluating manufacturing systems used to justify investment in manufacturing systems. Based on Basova et al. (2018) and Stepanov et al. (2019), the main provisions for calculating the productivity of machining parts intensify cutting modes when choosing the optimal parameters of fixtures.

Many research efforts by Mehrabi et al. (2002), Setchi and Lagos (2004), Hasan, Jain and Kumar (2014), and Förstmann et al. (2017) confirmed that equipment was essential for modern production. Thus, the requirements for accuracy, flexibility, rigidity, performance, and reliability are paramount and affect the effectiveness of manufacturing processes.

Ji et al. (2013) offered an effectiveness-driven modular design method that considers all effectiveness scenarios and balances the granularity and composition of modules among all possible forms during the clustering process to maximise the effectiveness of modules throughout the product life-cycle as much as possible.

Sonmez et al. (2019) found that the overall equipment effectiveness was considered a performance indicator for manufacturing equipment. Particularly, two types of uncertainty are considered in production, namely, speed and stoppage duration, which are used to calculate components of the overall equipment effectiveness.

Sarker et al. (2001) made a critical review and a comparative study of different grouping efficiency measures. Special emphasis was given to evaluating clustering solutions in the block-diagonalisation of the machine-part incidence matrix.

Li et al. (2007) proposed using the weighting factor for the incidence matrix, thus defining a new measurement of efficiency for multi-dimensional group technology. The investigation into modern experience has shown that many studies focused on efficiently functioning manufacturing systems.

Neely (1999) noted that group technology positively impacted on cost-based efficiency analysis of fixtures, making the design more efficient in terms of quality and productivity.

McIntosh et al. (2000) examined that the trend to reduce the cost and time in fixture design positively influenced the use of metal-cutting equipment, which enabled a continuous flow of production. Elkins et al. (2004) focused on the cost and time effectiveness in using flexible manufacturing systems in the automotive industry.

According to Sethi and Sethi (2001), in multi-product manufacturing, the variety of products requires a flexible response by the production systems without compromising cost-effectiveness.

Brettel, Klein and Friederichsen (2016) stated that the fast reconfiguration of systems and processes allowed maintaining excellent product performance at low costs.

Erdem et al. (2017) highlighted that the efficiency of a flexible fixture is a multi-dimensional task. However, their overall cost depends on investment and setup costs, which have a negative effect on efficiency while increasing.

However, no single approach considers the cost of time, the cost of implementing the manufacturing process, and the batch value of parts production when machining complex parts using flexible fixtures. This substantiates the relevance of the chosen research direction, and the list of research tasks is formed.

2. Research methods

The scope of the effective use of equipment is a set of parts produced by a given machine at a minimal cost compared to the cost of production on another machine or a group of machines that correspond to the technological problem according to specified production conditions.

The same part can be produced on different pieces of equipment designed for machining under different production conditions. In each case, the choice of equipment determines the efficiency of the manufacturing operation. If the use of different equipment can ensure the machining of parts of the required quality, the most effective equipment should be chosen based on economic indicators.

The scope of the effective use of equipment is established by comparing competing variants based on the technical and economic model, which considers the machining of parts of identical batches under the conditions of multiproduct manufacturing and compares only operations of machining of parts with different indicators.

A single economic indicator should assess the efficiency of the manufacturing process — the cost of machining (C), which considers the cost of time (T), the cost of manufacturing process implementation (S), and the batch size (N). Among the options of manufacturing processes for the manufacture of parts, the one that provides the lowest cost of machining is considered to be effective

$$\mathrm{C(T, S, N)} = \min\{\mathrm{C_{typ}}; \mathrm{C_{prop}}\} \tag{1}$$

The machining cost is calculated for the typical (C_{typ}) and the proposed (C_{prop}) manufacturing processes according to the proposed dependence:

$$C_{\text{typ.;prop.}} = \sum_{j=1}^{f} \sum_{i=1}^{m} C_i^{<j>} \tag{2}$$

where f — the number of fixtures for the implementation of the manufacturing process; m — the number of operations of a manufacturing process; j — number of fixtures for realising the considered manufacturing process; i — the operation number of the considered manufacturing process.

For the conditions of multiproduct manufacturing, it is advisable to estimate the cost of machining considering the cost of power energy E, depreciation of equipment A, operation of fixtures F and cutting tools R

$$C = E + A + F + R \tag{3}$$

The formula calculates power energy costs

$$E = P_{en} \cdot N_d \cdot K_N \cdot T_c / (K \cdot 60) \tag{4}$$

where P_{en} — the cost of 1 kW of power energy, UAH; N_d — established power of electric motors of the machine, kW; K_N — load factor by power (0.6–0.9 — for roughing operations, 0.3–0.6 — for finishing operations); T_c — cutting time, min; K — coefficient that considers different costs (0.9–0.95).

The formula calculates equipment depreciation costs

$$A = P_e \cdot K_a \cdot T_{mc} / (F_t \cdot K_e \cdot 60) \tag{5}$$

where P_e — book value of equipment, UAH; K_a — depreciation coefficient, which determines the payback period of the equipment (0.1–0.15 — for special equipment, 0.15–0.2 — for the main type of machines)); T_{mc} — the machining-calculation time of operation, min; F_t — actual annual fund of equipment operation, hours; K_e — equipment load factor.

The formula calculates the cost of operating the fixtures

$$\mathrm{F} = \mathrm{P_f} \cdot (\mathrm{a} + \mathrm{b}) / \mathrm{N} \tag{6}$$

where P_f — the cost of the fixture, UAH; a — depreciation coefficient (0.3–0.5); b — current repair cost coefficient (0.1–0.2); N — number of batch parts for which the machine tool is intended.

Given that the same machining conditions and cutting tools are used for both variants of the manufacturing processes, operating costs of the cutting tools are assumed to be the same for both variants and are not considered in further calculations.

A mathematical model is obtained by substituting formulas (4)–(6) in (3) and performing certain mathematical transformations, as well as allocating time costs (T_c, T_a, T_p), the cost of implementation of manufacturing processes (S_1, S_2, S_3) and the batch size (N),

$$\mathrm{C_i^{<j>}} = \mathrm{T_{ci}^{<j>}} \cdot \mathrm{S_{1i}^{<j>}} + \left(\mathrm{T_{ci}^{<j>}} + \mathrm{T_{ai}^{<j>}} + \mathrm{T_{pi}^{<j>}}\right) \cdot \cdot \mathrm{S_{2i}^{<j>}} + \mathrm{S_{3i}^{<j>}} / \mathrm{N^{<j>}} \tag{7}$$

where $T_{ci}^{<j>}$— the elements of the matrix of the cutting time by size $m \times f$; $T_{ai}^{<j>}$ — the elements of the matrix of the auxiliary time by size $m \times f$; $T_{pi}^{<j>}$ — elements of the matrix of preparatory time by size $m \times f$; $S_{1i}^{<j>}$ — elements of the matrix of power energy costs for the implementation of the manufacturing process by size $m \times f$; $S_{2i}^{<j>}$ — elements of the matrix of equipment depreciation costs by size $m \times f$; $S_{3i}^{<j>}$ — elements of the cost matrix for the design and operation of fixtures by size $m \times f$.

Thus, the task is to choose the manufacturing process, which allows incurring the minimum cost of machining among the proposed options. The problem of minimising the cost function (7) is solved consistently for competing variants of the manufacturing process, considering technical limitations. The results were evaluated using comparative economic efficiency, the ratio of costs in the implementation of typical and proposed manufacturing processes comparative economic efficiency, the ratio of costs in the implementation of typical and proposed manufacturing processes

$$E = {}^{C_{typ}}/_{C_{prop}} \tag{8}$$

3. Research results

The practical implementation of the proposed mathematical model on the example of batches of differently configured plugs illustrated that the effective implementation of the proposed manufacturing process differed depending on the number of types and sizes of machined parts as changes in time consumption.

When machining fork-type parts, the proposed manufacturing process based on the multiaxis machining is effective provided that the batch volume of the workpiece does not exceed 50 pcs. (Fig. 1). For these conditions, the cost of operating flexible fixtures is lower than the cost of a set of dedicated fixtures.

The ability to process several nomenclatures in flexible fixtures allows expanding the scope of the effective use of proposed manufacturing process to 66 and 71 parts in the batch with two and three nomenclatures of workpieces, respectively (Fig. 2, 3). The cost of machining according to the proposed manu-

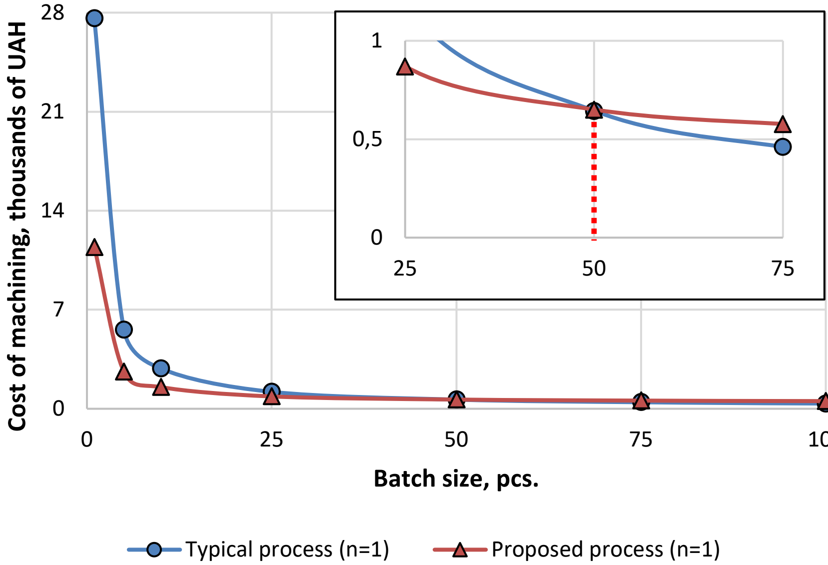


Fig. 1. Cost of machining parts depending on the batch size when machining one nomenclature of parts

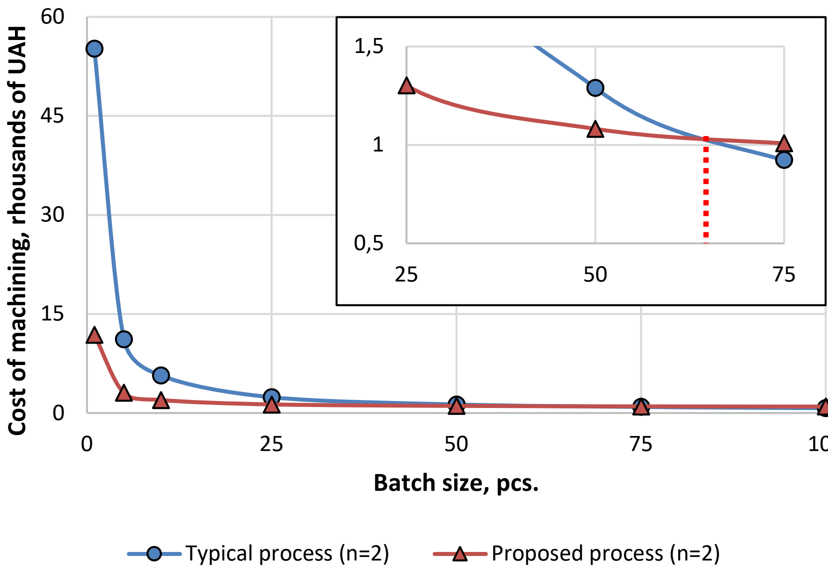


Fig. 2. Cost of machining parts depending on the batch size when machining the two nomenclatures of parts

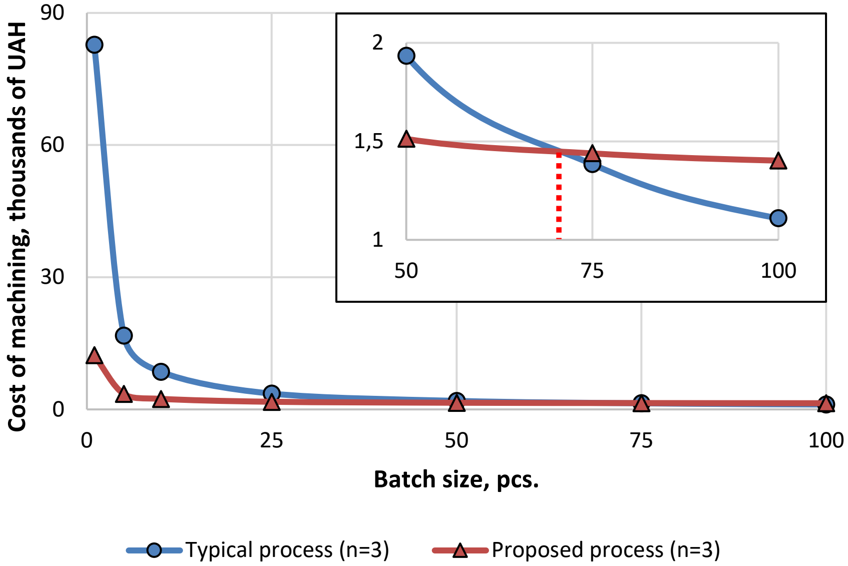


Fig. 3. Cost of machining parts depending on the batch size when machining the three nomenclatures of parts

facturing process is reduced, and the comparative economic efficiency equals 1.19 and 1.28 for two and three nomenclatures of machined parts, respectively, when calculating for a batch of parts with 50 pcs.

Thus, the determined general tendency is to increase the batch size that can be machined according to the proposed manufacturing process while increasing the number of fixture nomenclatures.

The productivity of machine tools significantly depends on the share of the cutting time in the structure of machining time. It has been established that the cutting time influences the choice of a manufacturing process and the determination of the effective scope's limit.

Further research revealed a general trend that a shorter machining time indicates the effectiveness of the proposed manufacturing process. E.g., the research dependencies of the cost of machining on the batch size when machining one to three nomenclatures of parts at Tc=1 min allowed to establish that the proposed manufacturing process was useful when machining a batch of parts up to 90 pcs. Increasing the number of standard sizes of parts allows expanding the scope of the effective use of multiaxis machining centres to 119 and 129 parts for two and three nomenclatures, respectively. Increasing the batch of parts with an increasing number of nomenclatures is insignificant.

Thus, the general tendency is determined to increase the batch size that can be machined according to the proposed manufacturing process while increasing the number of fixture nomenclatures.

The productivity of machine tools significantly depends on the share of the cutting time in the structure of machining time. It is established that the cutting time influences the choice of the manufacturing process and the determination of the effective scope's limit.

Further research revealed a general trend that a shorter time of machining indicates the effectiveness of the proposed manufacturing process. E.g., the research dependencies of the machining cost on the batch size when machining one to three nomenclatures of parts at Tc=1 min allowed to establish that the proposed manufacturing process was useful when machining a batch of parts up to 90 pcs. Increasing the number of standard sizes of parts allows expanding the scope of the effective use of multiaxis machining centres to 119 and 129 parts for two and three nomenclatures, respectively. Increasing the batch of parts with an increasing number of nomenclatures is insignificant.

According to the production conditions at the cutting time T_c=10 min, the proposed manufacturing process is useful when the batch size comprises 70 pieces. When machining a batch of parts of several sizes, the efficiency limit is shifted to increase the batch size. The efficiency of the proposed manufacturing process with two nomenclatures of parts equals up to 95 pcs., and up to 103 pcs. in the case with three nomenclatures of parts.

The use of a typical manufacturing process is cost-effective for long-term machining of parts, e.g., at T_c=50 min. For these conditions, the limit is the batch size with more than 37 pcs. for one nomenclature, 50 pcs. — two nomenclatures, 54 pcs. — three nomenclatures.

The reduction of the share of auxiliary time in machining time is considered a tendency in metalworking. For the workpieces under consideration, this share equals 70–450% for a typical manufacturing process and 30–130% for the proposed manufacturing process. The influence of auxiliary time on the cost of machining is investigated, and the useful scope of the manufacturing process is established under the condition of the same value of auxiliary time for both investigated variants. With the share of auxiliary time comprising 25% of the cutting time norm, the efficiency of the proposed manufacturing process is observed when the batch size reaches up to 51 pcs. When comparing the production conditions, the effectiveness of the proposed manufacturing process is observed at the rate of auxiliary time up to 8 min.

The analysis of machining conditions of parts at the norm of auxiliary time of 50% and 150% of the norm of the cutting time confirmed that the limit of efficiency of using the proposed manufacturing process decreases at the increase of the auxiliary time norm. It is proved that when machining several sizes of parts, the scope of effective use is shifted in the direction of increasing the batch size, in particular, by 34% for two nomenclatures of parts and 45% for three nomenclatures.

The analysis of the effectiveness of the proposed manufacturing process, depending on the preparatory time, allowed determining the limits of the effective use of different manufacturing processes. The same norm of preparatory time for the considered manufacturing process is accepted in calculations. The results confirmed the general trend that the effectiveness of the proposed manufacturing process is proven for machining small batches of 48 pcs., 34 pcs., and 22 pcs. at the norms of preparatory time, and they comprise 75%, 150%, and 300% of the cutting time norm, respectively.

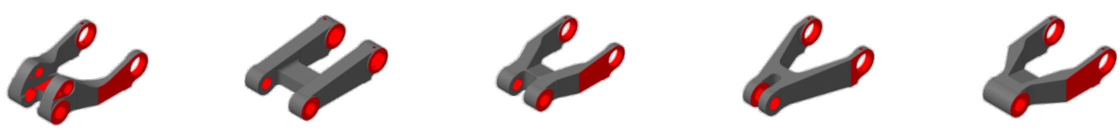
Studies show that the proposed approach to using flexible fixtures for machining of several nomenclatures of parts allows increasing the batch size of parts by 32% when machining parts of two nomenclatures or by 44% when machining parts of three nomenclatures.

4. Discussion of the results

Ganesan and Mohankumar (2013) found a significant impact made by the minimum operating time, production cost, and tool wear. Dehtiarov (2017) evaluated the cost of machining based on a comparative analysis of the effectiveness of different fixture systems (dedicated fixture, modular fixture, and modular adjustable fixture). His research mainly focused on the cost of design, assembly, and batch size. However, time costs were not considered. Also, Erdem (2020) proved that the cost of a fixture depended on the hardware cost of a flexible fixture, the cost of setup and external equipment needed for a flexible fixture, the software development cost and the software development time, and the total cost allocated to a flexible fixture. Therefore, the cost of machining should be calculated considering time costs, particularly cutting time, auxiliary time, and preparatory time. It is proved that multiproduct manufacturing needs quick changeovers to meet industry challenges and market needs.

The proposed methodological approach was verified on machining fork-type parts with similar design and technological features combined in a group. This group consists of five different fork-type parts (Fig. 4). The total number of parts in this group is 150 pcs.

A comparative analysis of typical and proposed manufacturing processes was performed for two cases, namely, machining one part and machining a batch of parts (Table 1). Based on the calculations, machining costs are different when using different fixtures under the same production conditions. A batch size significantly influences the choice of the manufacturing process. It was assumed that a typical manufacturing process required five dedicated fixtures, which allowed performing all drilling, milling, and boring operations. The implementation of the



a) b) c) d) e)

Fig. 4. Typical fork-type designs

Tab. 1. Comparison of the effectiveness of the proposed and typical manufacturing processes

Fork-type design (according to Fig. 4)	Name and code of the part	Batch size, pcs.	Manufacturing process	Cost, UAH	Comparative economic efficiency
a	Plug 99408076	30	Typical	1011.28	1.27
			Proposed	797.38	
b	Plug 3721-4511	40	Typical	782.12	1.05
			Proposed	745.0	
c	Plug 99408076-2	70	Typical	487.48	0.83
			Proposed	587.86	
d	Plug 73.02.34-01	100	Typical	369.62	0.68
			Proposed	540.72	
e	Plug 120.3-88.01.05	10	Typical	2844.62	1.86
			Proposed	1530.72	
a, b, c, d, e	Batch of parts	250	Typical	5495.11	2.5
			Proposed	2197.58	

proposed manufacturing process needs one flexible fixture, which allows performing multiaxis machining. The effectiveness of the proposed manufacturing process was substantiated by comparing the typical and the proposed manufacturing processes when machining fork-type parts (Fig. 4 a, b, e) with a batch size of 30 pcs., 40 pcs., and 10 pcs., accordingly. In these cases, the cost of machining is lower than for the typical manufacturing process. Therefore, comparative economic efficiency is higher than 1. When machining fork-type parts (Fig. 4 c, d) with batch sizes of 70 and 100 pcs., the cost of a typical manufacturing process is lower, as the costs are calculated for the entire batch of parts.

In the traditional approach, the cost of machining for a batch of parts is calculated as the sum of the costs of a typical manufacturing process for each considered part. As known, a flexible fixture ensures the setup of similar parts; therefore, all five configurations of the described fork-type parts can be set up in one fixture. In this case, the cost of machining is calculated for the batch size of 250 pcs. Based on the calculations, the advantage of the proposed manufacturing process is undeniable. A particularly significant contribution is made by introducing flexible fixtures and allowing multiaxis machining of parts of several nomenclatures. The comparative economic efficiency equals 2.5. Thus, according to the calculated data, the proposed manufacturing process efficiency is inapplicable for all designs of parts and their batch sizes. It was established that the highest efficiency of the offered manufacturing process was reached with batches of up to 20 pieces.

Conclusions

The efficiency of implementing flexible fixtures depends on various factors. The paper presented a mathematical model for evaluating the efficiency of manufacturing processes involved in the machining complex parts using flexible fixtures at the cost of machining. The cost of time, the cost of implementing the manufacturing process, and the batch size were considered.

Based on the paper, flexible fixtures are effective for machining small batches of parts with short-term machining and frequent readjustments to new workpieces. A tendency has been established that a higher number of nomenclature of parts contributes to expanding the scope of the effective use of flexible fixtures. Further research will be focused on implementing the proposed approach to other types of parts in multiproduct manufacturing.

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Light Fidelity (Li-Fi) overview and investigation into connection speed

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ABSTRACT

The overarching aim was to reduce the frequency of connection failures that occur due to the connection speed and reliability, and identify, characterise and optimise the key process input variables (KPIVs). An experimental research approach with an inbuilt planned manipulation to one or more variables in the experimental data set was adopted. Key elements of the Six-Sigma methodology were applied to resolve the issue of high failures due to connection speed and reliability between two Li-Fi transceivers. KPIVs were successfully identified, characterised and optimised to implement a permanent corrective action to ensure a reduction in connection failures from 17% to 0%. The alignment between two Li-Fi transceivers along with Li-Fi cut-out was found to be critical in achieving good connection speed and reliability. The interference due to ambient visible spectrum lighting found to be statistically insignificant. This study explored the application and benefits of accessible wireless data communication technologies. Moreover, it sheds light on the probable factors that may influence Li-Fi connection speed and areas for future research. The current research provides a Six-Sigma based solution to high connection failure rates while using an infrared-based Li-Fi transceiver. Results also offer insights into the analytical tools that were found to be effective during the problem-solving process.

KEY WORDS

Light Fidelity (Li-Fi), Six-Sigma, defect reduction, wireless communication

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Introduction

Over the past decade, the demand for digital services has grown at an astonishing pace, with the number of worldwide Internet users burgeoning significantly. The demand for data and digital services is also expected to grow exponentially, with global Internet traffic doubling by 2022 to 4.2 zettabytes per year. The number of mobile internet users is projected to increase from 3.8 billion in 2019 to 5 billion by 2025, and the volume of Internet of Things (IoT) con-

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nections (interconnected physical objects via the Internet) is expected to double from 12 billion to 25 billion (Cisco, 2019). These changes are driving exponential growth in the demand for data centre and network services (Sumits, 2015). The currently available radio spectrum is below 10 GHz (cm-wave communication), which is insufficient to deal with the demands arising out of these mounting changes and is thus put under severe strain. To deal with this constraint, the wireless communication industry is forced to explore alternative options that are beyond the range of radio spectrum, in particular infrared and visible light spectrums (Tsonev, Videv & Haas, 2013).

One such possible substitute and an emerging Visible Light Communication technology is Light-Fidelity (Li-Fi) that allows wireless transfer of data at high speeds through visible light, ultraviolet and infrared spectrums. The underpinning principle is simple. It relies on the speed of the transmitter modulator that switches a light-emitting diode (LED) on and off so quickly that it is undetectable by the human eye (Hass, 2018). A photodiode on the receiver picks up the light and converts it into electrical impulses. The study presented in this article explores the application of Li-Fi when communicating with Automated Guided Vehicles (AGV) wirelessly. Previously, AGV were connected via Wi-Fi communication technologies with the vehicle for route administration or any other control systems. Putting aside the sustainability aspects of wireless data services over radio frequency, the issue still exists in relation to multiple parallel participants in a radio-based network can interfere and alter the reliability of the existent data links (Tsonev et al., 2013). Further, Wi-Fi penetration across walls poses a network security threat. Considering these challenges, secure faster connectivity and sustainable option in terms of Li-Fi was considered by the organisation. As Li-Fi is a relatively new technology with limited applied knowledge, a number of issues relating to connection speed and reliability were experienced. The study presented here aims to identify, characterise and optimise key process input variables (KPIVs) to achieve optimum connection speed and reliability. This study was conducted in a UK-based, global technology company renowned for its end-to-end warehousing solutions. A graphical representation of how data transmission is done between AGV and System Li-Fi transceiver is shown in Fig 1. A transceiver is a device that acts as a transmitter and receiver for dual communication purposes.

With the implementation of the next generation AGV, a high failure rate due to connection speed and reliability was experienced. For AGV to be operational, key information like route-map, firmware etc. are transferred onto the system using a Li-Fi transceiver. However, 17% of AGV were failing during this stage, making them non-functional and affecting site operational efficiency severely. So far, no scientific study of this nature has been published; thus, the findings are promising in terms of revealing novel insights into how variation caused by manufacturing and installation process can be resolved using the Six-Sigma methodology.

1. Literature review

Automated solutions are often employed by the Intralogistics industry to achieve a more flexible, reduced rate of human errors and continuous flow of goods. One of the major developments in this indus-

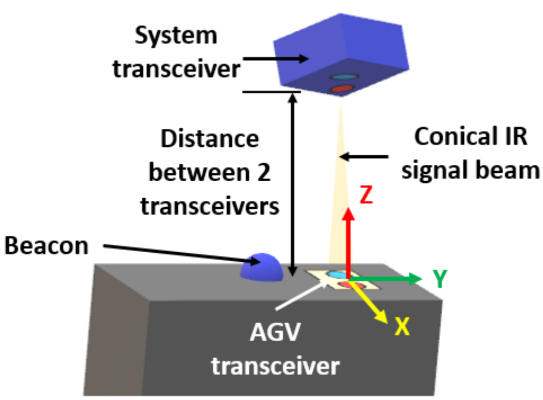

Fig. 1. Graphical representation of Li-Fi communication between system and AGV

try has been the use of automated guided vehicles to control the flow of goods where human intervention could be impractical or cost-ineffective, e.g., working in a sub-zero chill refrigeration environment. AGV are typically connected via WLAN or other radio-based communication technologies with the vehicle for route administration or any other control systems. However, many parallel participants in a radio-based network can cause interference and affect the reliability of data links. Also, the increasing demand for wireless data communication via an available radio-frequency spectrum is running out of capacity and becoming insufficient for catering to the increased needs. Several independent warnings have been raised about the saturation of network spatial capacity despite the new technological advancements in the field of wireless communication via the RF spectrum (Ofcom, 2014). Furthermore, spatial reuse and co-channel interference are not ideal for automated solutions, especially while controlling AGV. This presents itself as a huge challenge for the wireless communication industry, thus creating an urgency to explore alternative parts of the electromagnetic spectrum which can be used to reduce strain on the already overcrowded RF spectrum (Tsonev et al., 2013).

A common substitute presented by the wireless communication industry is the use of Light-Fidelity (Li-Fi) of an optical wireless (OW) or visible light communication (VLC) system. This is of particular interest as it is used in the study presented in this article. The VLC is a technology that includes the transmission of data through free space or fibre using wavelengths ranging from infrared (IR) to ultraviolet (UV), including visible light spectrum (Haas & Cogalan, 2019). The Li-Fi branch of VLC is like the Wireless Fidelity (Wi-Fi) that allows electronic devices to connect wirelessly to the network. The Li-Fi system uses high-intensity light source like LED bulbs that are controlled by the driver-circuit, which encodes data and transmits it by switching the LED on and off, similar to Morse code. The only difference is that the rate at which it flicks LED on and off is indiscernible to human perception and required an optical sensor to receive/decode the data (Elgala, Mesleh & Haas, 2011).

Research, development and standardisation of VLC were led by the Visible Light Communication Consortium (VLCC) in Japan, resulting in two visible light standards labelled as JEITA CP-1221 and JEITA CP-1222 by Japan Electronics and Information Technology Industries Association (JEITA). In 2011, IEEE 802.15.7–2011 — IEEE Standard for Local and Metropolitan Area Networks--Part 15.7: Short-Range Wireless Optical Communication Using Visible Light was also published. Comparing Li-Fi to other data communication technologies, like Wi-Fi and Ethernet, it is relatively new and came into existence during 2011. On the other hand, the Ethernet is a well-established LAN technology that was commercially released during 1980 as IEEE802.3. The Ethernet speed based on the latest IEEE802.3ck standard can achieve upto100Gb/s. Other dimensions that interested researchers are data transmission medium, security, range (10 metres for Li-Fi and 100–185 metres for Ethernet), reliability (high vs very high for Li-Fi and Ethernet, respectively), connection (Li-Fi being wireless and Ethernet is wired) and cost (Li-Fi being the cheapest). Table 1 offers a systematic comparison between these three data communication technologies as presented in published literature (Elbasher, Mustafa & Osman, 2015; Gent, Downing & Dalton, 2003; Giuseppe et al., 2003) on these metrics.

For the study presented in this article, data communication is carried out on moving devices; thus, wireless technology was necessary. For this reason, despite all the benefits that the Ethernet LAN offers, it was not considered a good fit for this purpose. Further, security and reduced interference between cross channels gave Li-Fi an edge over Wi-Fi. The Li-Fi technique has a wide range of application across distinct sectors. E.g., in a research published by Sudha (2016) and during a project titled AAL X AAL by the VDA group, Li-Fi was used to enable data connectivity that does not produce electromagnetic pollution and which can potentially be detrimental to life-saving machinery like MRI scanners. A number of patient data metrics such as temperature, heartbeat, glucose and respiratory were collected using sensors and transmitted to a graphical representation on the PC. In the end, the KPI of reducing interference to medical equipment was effectively achieved. In other studies, Li-Fi was applied for improving reliability collaboration, security measures and interference-free traffic management system (Singh et al., 2017; Wang et al., 2017). In the study by Singh et al. (2017), Li-Fi was used to manage a vehicle toll collection system transmitter was installed on the vehicle sending encrypted data such as vehicle registration number, personal identification number and payment gateway password via LED. It helped develop a seamless automated system. Similarly, Wang (2017) created a smart transportation model, where traffic data

Tab. 1. Comparative Summary of common data communication technologies

Key Parameters	Li-Fi (Light Fidelity)	Wi-Fi (Wireless Fidelity)	Ethernet
IEEE Standards	802.15.17	802.11b	802.3
Frequency	10 x Tera Hz	2.4 GHz	-NA-
Data Transmission Medium	Light	Radiofrequency	UTP - STP – OF
Speed	1 - 3.5 Gbps	25-250 Mbps	10-1000 Mbps
Range	10 meters	20-100 Meters	100 - 185 Meters
Security	High (direct line of sight required)	Medium (can penetrate through walls)	High (physical connection required)
Reliability	High	High	Very High
Release Date	2011	1990	1980
Connection	Wireless	Wireless	Wired
Cost	Cheapest	Most Expensive	Cheaper than Wi-Fi

was managed autonomously in real-time. The vehicle data relating to its speed was monitored, and the smart vehicle was controlled by the output from the traffic management system. The Li-Fi technique exhibited tremendous potential in managing traffic with fewer accidents.

With the use of Li-Fi as an optical data transmission technology, stable interference-free data links can be set up, thus ensuring secure data transmission at all times. An additional advantage of Li-Fi is that the parallel operation of many vehicles utilising a similar, stable bandwidth can be realised. However, not much evidence was found on the use of IR based Li-Fi system and how to optimise or improve connection and data transfer speed. The key issue of investigation in the current research was of high variation in the connection speed and poor reliability amongst AGV. To resolve this problem, the Six-Sigma technique was employed as statistically proven to be valid and objective. Key elements of the Six-Sigma DMAIC (Define, Measure, Analyse, Improve, and Control) methodology were applied to resolve the issue of high failures due to low connection speed and poor reliability between two Li-Fi transceivers. The problem statement for the current project was that 17% of AGV were failing to connect at XX (confidential) site using Li-Fi that was further resulting in a strain on the bottleneck process. The overall aim of this research was to reduce AGV connection failures due to Li-Fi connection speed and reliability.

Specific research objectives:

- To identify the factors responsible for high connection failure rates.
- To characterise and optimise KPIVs to achieve optimum connection speed and reliability.
- To implementing sustainable long-term process improvements that will reduce the defect rate to <1%.

2. Research methods

An experimental research design with an inherent manipulation of the experimental variables was adopted in the current research. Six Sigma is a quality improvement technique that has been shown to be scientific, rigorous, and systematic. It is based on the careful integration of a range of statistical methods that enables new developments and error reduction in existent phenomenon (Breyfogle et al., 2001). The range of benefits that implementation of the Six-Sigma methodology yields can be mapped along economic, individual, and organisational dimensions as it optimises resource usage, enhances user experience, and elevates the skill repertoire of the person in charge (Su & Chou, 2008; Yang & Hsieh, 2009). Supporting evidence for the excellence of the Six-Sigma technique has been demonstrated by several industries, such as chemical (Doble, 2005), manufacturing (Gangidi, 2019; Sharma, Sahni & Sharma, 2020), financial (Brewer & Eighme, 2005), information technology (Arul & Kohli, 2004; Edgeman, Bigio & Ferleman, 2005), automobile (Gerhorst et al., 2006), and senior administration (Furterer & Elshennawy, 2005).

A team of qualified technical staff was gathered for the implementation of the technical aspects of this project, and a certified Six-Sigma black belt specialist was appointed for overlooking the implementation of the Six-Sigma framework. A Six-Sigma process of DMAIC, based on Deming's Plan-Do-Check-Act cycle for improving existent processes, was selected for this study. The DMAIC strategy consists of five stages: Define, Measure, Analyse, Improve, and Control.

Define is the first and foremost stage which involves operationalisation of the project's objectives and delineation of critical to quality (CTQ). The

CTQs are formulated in strict accordance with customers' preferences.

Measure stage consists of data collection and a systematic assessment of the key components of the project plan.

Analyse phase is concerned with statistical evaluation of trends in data and serves as pilot testing results that facilitates future replications of valid and quantifiable models.

Improve is the implementation patch which aims at completing the set objectives and achieving the desired benefits.

Control refers to documentation of every single detail of the previous so that successful episodes would serve as guidelines while failures would provide insights into potentially fraught procedures for effective planning and monitoring of future projects.

3. Research results

This section presents key outcomes from the DMAIC phases of the improvement project with an enhanced focus on the Analyse and Improve phases. At the completion of the Define and Measure phases, "connection speed" was identified as a Key Performance Indicator (KPI) and KPIVs that can affect connection speed are shown using a Fishbone Diagram in Fig. 2.

Post segregation, it was identified that the failure rate was considerably higher for the next generation AGV. So, gaining an understanding of the differences between those two AGV emerged as a top priority for future investigation. The KPIV list from the Fishbone Diagram was narrowed down to 6 factors. L36 (2^3, 3^3) Taguchi Design of Experiment (DoE) was deemed appropriate to evaluate the impact of KPIVs on connection speed with the CNX diagram shown in Fig. 3.

Further understanding into alignment/position experimental variables (X, Y & Z-pos) can be gained from Fig. 1 of the introduction section. To achieve different levels of experimental variables for the DoE was straightforward except the vibration due to the unavailability of the measurement system. To overcome this challenge, two levels of vibration were selected. Firstly, when no AGV were operational, producing negligible vibration, and secondly, when multiple AGV were running around the test set-up. With the test set-up confirmed, Taguchi DoE was conducted, and the main effects plot for the mean connection speed are shown in Fig. 4. Key factors influencing connection speed were the positions (X, Y, Z Pos) or an alignment between the two Li-Fi transceivers along with AGV type. The impact of each factor on connection speed is inferred from the "delta" (Table 2), based on which they are rank-ordered. The key difference between the two AGV was the installation position of the Li-Fi transceiver.

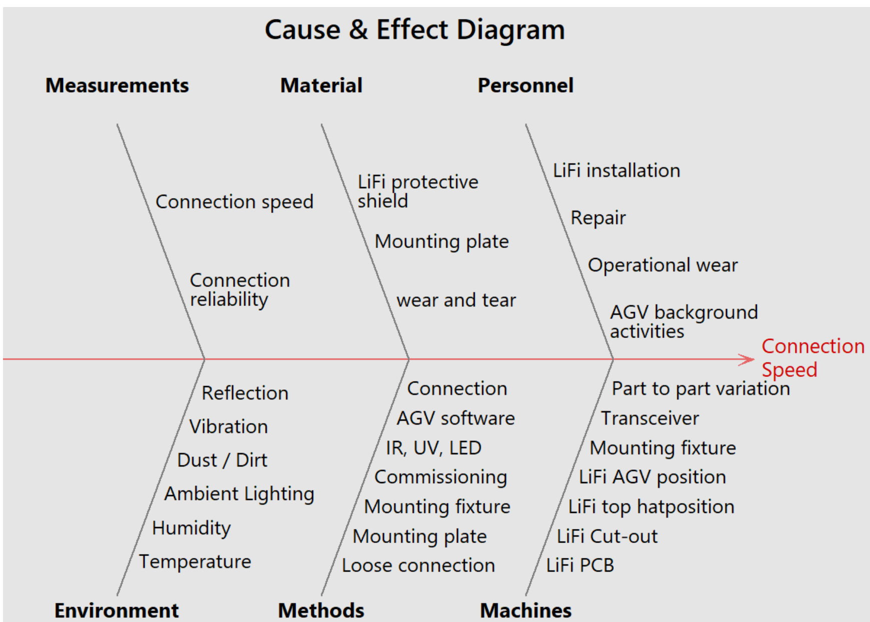

Fig. 2. Fishbone Diagram for connection speed

Volume 13 • Issue 1 • 2021

After gaining relevant insights from the Taguchi DoE, the next set of experimental designs were focused on the Li-Fi position and aimed at making designs more resilient to the Li-Fi installation position on the AGV. As Z-pos or distance between the transceivers was the most important factor, the optimum setting without interaction were found to be 240mm via One Factor At a Time (OFAT) testing. The next set of tests were conducted to evaluate the impact of surface reflection, AGV type and Cut-Out Size on connection speed in conditions where X, Y position is perfectly aligned, and Z-position is fixed at 240 mm. A full factorial design with 3 factors and 2 levels was conducted with the Main Effects Plot. The model summary is shown in Fig. 5 and Table 3, respectively. It is evident that in cases where the Li-Fi position is at an optimum position, none of the other factors had a statistically significant impact on the connection speed. Moreover, R-sq (adj) for the model is zero and the p-value for all the factors is < 0.05.

Reflecting on the analysis conducted so far, it can be argued that the optimum connection speed could be achieved by controlling the Li-Fi position. However, the margin for error was only ± 5 mm in X–Y alignment, which was difficult to achieve consistently during the installation and operation processes. So, the next set of experiments included X, Y, Z-pos and cut-out size to identify the tolerance for the X, Y & Z positions. Additionally, a 4 factor 2 level Full Factorial DoE with centre points was conducted with the main effects plot. The model summary is shown in Fig. 6 and Table 4, respectively.

A strong regression model with R-sq(Adj) of 90.61% was achieved with a combination of four factors tested during the experiment suggesting most of the process variation can be controlled via these fac-

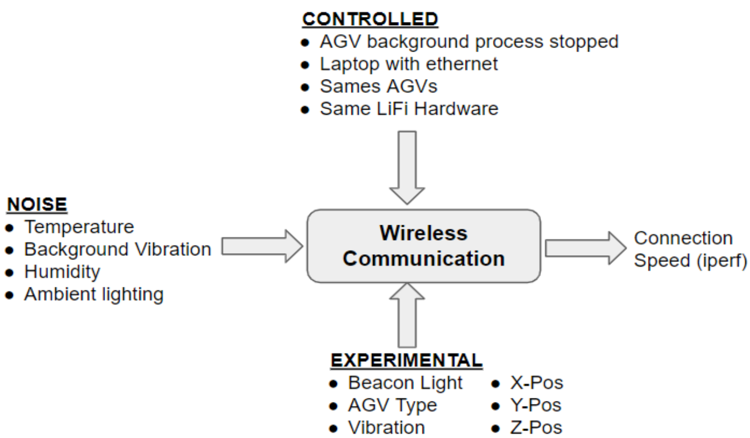

Fig. 3. CNX diagram for Taguchi DoE

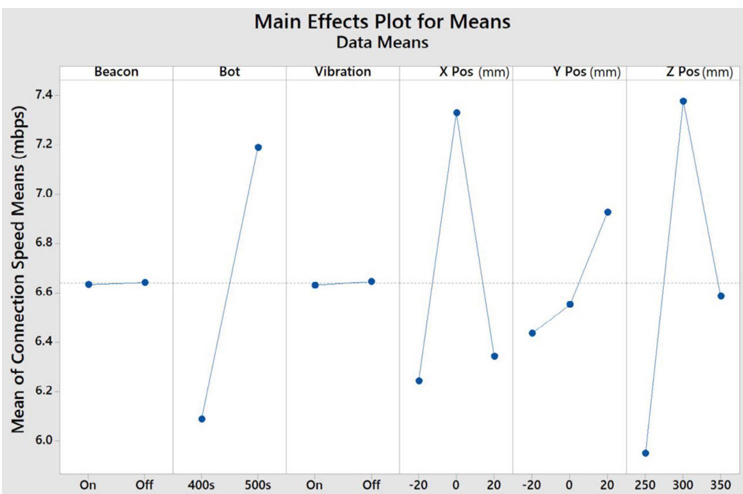

Fig. 4. Main effects plot for mean connection speed

Tab. 2. Response table for mean connection speed (in mbps)

Level	Beacon	AGV	Vibration	X Pos	Y Pos	Z Pos
1	6.634	6.088	6.632	6.243	6.437	5.951
2	6.642	7.190	6.646	7.329	6.553	7.378
3				6.344	6.927	6.587
Delta	0.008	1.102	0.014	1.087	0.490	1.426
Rank	6	2	5	3	4	1

Tab. 3. Model summary and coded co-efficient for the connection speed

S	R-sq	R-sq(adj)	R-sq(pred)
0.156972	7.92%	0.00%	0.00%

Term	Effect	Ratio Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant			2.11936	0.00285	744.51	0.000	
Reflection	0.00181	1.00182	0.00091	0.00285	0.32	0.752	1.00
AGV Type	-0.00204	0.99796	-0.00102	0.00285	-0.36	0.722	1.00
Cut Out	-0.00165	0.99835	-0.00082	0.00285	-0.29	0.774	1.00
Reflection*AGV Type	-0.00539	0.99463	-0.00269	0.00285	-0.95	0.351	1.00
Reflection*Cut Out	-0.00177	0.99823	-0.00089	0.00285	-0.31	0.758	1.00
AGV Type*Cut Out	0.00263	1.00264	0.00132	0.00285	0.46	0.647	1.00
Reflection*AGV Type*Cut Out	-0.00632	0.99370	-0.00316	0.00285	-1.11	0.275	1.00

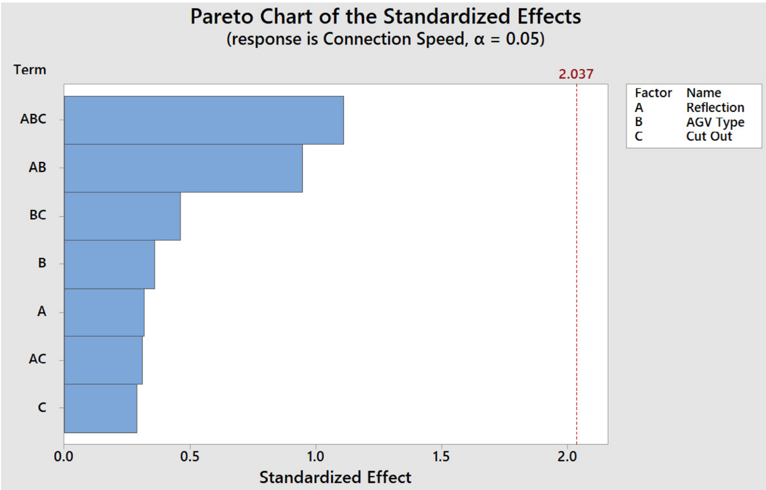

Fig. 5. Pareto chart of the standardised effect

tors. It was calculated (using the response optimiser of Minitab) that by introducing a cut-out, the alignment tolerance for the X, Y and Z position can be increased from 10 mm to 40 mm prior to obtaining a statistically significant change in the connection speed.

Increased tolerance in position was enough to accommodate manufacturing, installation and operational variations between the two AGV. The introduction of a bigger opening (cut-out) to receive and send a signal provided a robust design. Following parameters were used for an optimum set-up:

- Bigger Cut-Out
- X-Pos = -30 to 10 mm
- Y-Pos = -10 to 30 mm
- Z-Pos = 220 to 260mm

Pilot testing was conducted on this set-up using a single Li-Fi set-up but multiple AGV. Process capability, Cpk = 3.18, was much higher than the industry standard of 1.67, which suggested the robustness of the solution.

The new set-up has been rolled out to the entire site with over 20 Li-Fi set-ups and hundreds of AGV. It has been running for over three months, with

Tab. 4. Model summary and coded co-efficient for Connection speed

S	R-sq	R-sq(adj)	R-sq(pred)
0.929010	91.56%	90.61%	88.99%

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		5.579	0.147	37.98	0.000	
AGV Cut-Out	-3.992	-1.996	0.120	-16.64	0.000	1.00
Height	-0.757	-0.378	0.147	-2.58	0.013	1.00
X Pos	-0.720	-0.360	0.147	-2.45	0.018	1.00
Y Pos	3.702	1.851	0.147	12.60	0.000	1.00
Cut-Out*Y Pos	2.860	1.430	0.147	9.74	0.000	1.00
Ct Pt		1.436	0.254	5.64	0.000	1.00

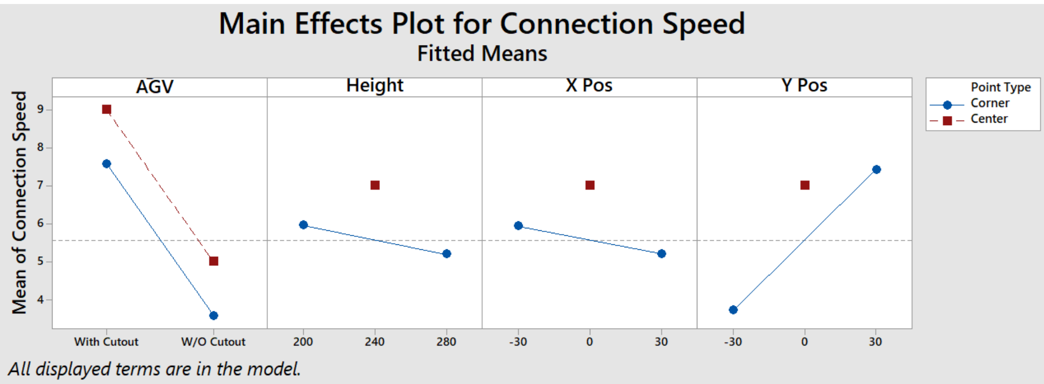

Fig. 6. Main effects plot for mean connection speed

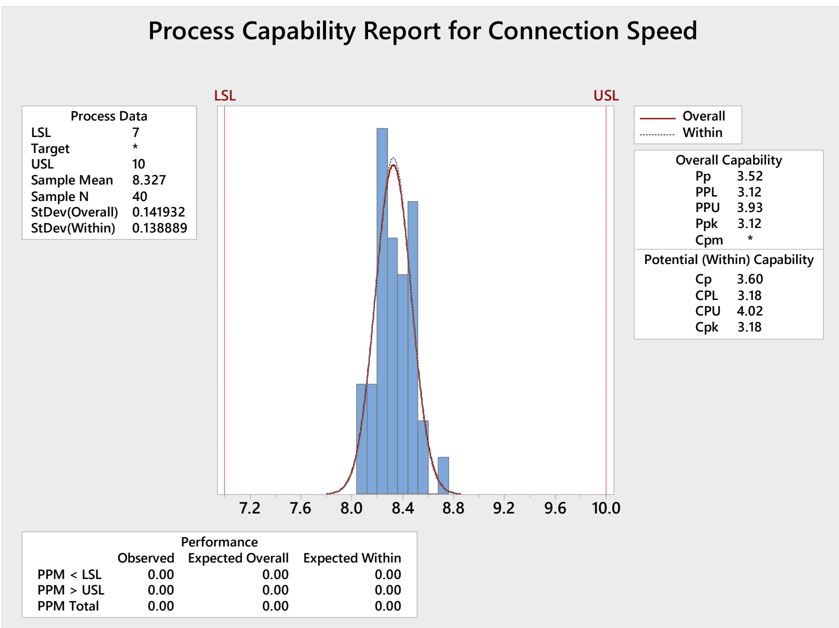

Fig. 7. Process capability of pilot testing

approx. of 4500 operations and zero connection failures observed so far.

4. Discussion of results

The research study presented in this article was successful in meeting all the set objectives. The failure rate occurring due to a loss of connection was reduced from 17% to 0% while maintaining a good process capability of 3.18. The current research paper aimed at the identification, characterisation and optimisation of the key input variables to achieve a robust solution. It is already known (Tsonev et al., 2013; Le Bas et al., 2015) that an alignment between two transceivers is crucial for the establishment of a reliable and high connection speed. However, published scientific literature did not reveal any details about the extent of a misalignment tolerated prior to its significant impact on connection speed. This gap in research could be attributed to the design's dependence on the Li-Fi product type (technology used) and application. Thus, a characterisation of the impact of Li-Fi transceiver alignment for the products used in the current study was of high relevance. It was found that the distance between two transceivers, when set at 240 ± 20 mm, could accommodate misalignment of ± 5 mm on the X & Y-axis without compromising the connection speed.

Another interesting finding from the current research was that an increase in the surface area that received and transmitted signal (cut-out) was critical for achieving a robust design that could deal with a higher tolerance for misalignment. In cases where the two transceivers were perfectly aligned, a bigger cut-out had no impact. However, in the current application, a misalignment between two transceivers could be as high as 20 mm due to operating and manufacturing variation. Thereby an increase in the cut-out, and with a ± 20 mm misalignment, the connection speed and reliability remained unaffected.

Other research studies (Pradhan, Kappala & Das, 2020; Sharma, Sanganal & Pati, 2014) have found that the communication channel may suffer from interferences caused by the ambient lighting conditions. A finding of great relevance was that the Li-Fi transceiver used in the current design remained unaffected by the visible ambient lighting even when placed in close proximity to the Li-Fi unit. It should also be noted that the product used in the current application is an infrared Li-Fi transceiver and not a LED version that has been cited as a potential cause of this deviation from the previously published research studies. Furthermore, since IR lighting is not used at this site, it wasn't considered necessary to evaluate its impact on signal interference.

Additionally, it should be noted that planning and administration of confirmation testing, and a pilot run after performing experimental design, especially screening tests, is strongly recommended. Supporting evidence for this recommendation is derived not only from the current research but from previously published literature as well (Sreedharan et al., 2019; Sharma, Sahni & Sharma, 2019). In the current experimental testing, ineffective results with no impact on the failure rates were observed, on the implementation of a pilot run that was based on the results from Taguchi screening DoE. The only promising insight gathered through the pilot run was of finding significant input variables. However, the inability to detect a significant interaction between the newly identified factors resulted in a non-optimum set-up. The next stage DoE was administered to characterise the key process input variables and their interactions. This aided in the creation of a significant regression model that resulted in an optimum set-up. Following this, another confirmation test and pilot experiments were conducted to validate the results. The significance of conducting a confirmation test and pilot experiments is, therefore, further endorsed by the current research results.

The issue of recurring failures was effectively prevented by the implementation of the Six-Sigma methodology, which further strengthens the current evidence on the wide scope of the Six-Sigma methodology in manufacturing operations (Swarnakar & Sekar, 2016; Sharma, Sahni & Sharma, 2019a). The issue of recurring connection failures was identified to be a constant source of restrictive strain on the bottleneck process, thereby resulting in a huge financial cost to the company and very high dissatisfaction amongst the users. The current research strategy, based on the Six-Sigma methodology, resulted in complete elimination of the failures occurring due to connection problems. Moreover, the current set-up has been running for a few months now, and no more cases of previously recurring failures have been observed since the implementation of the optimum set-up.

The current study did not explore the issue of interference in the communication channel caused by infra-red (IR) or ultraviolet lighting (UV), as not even a single source of IR/UV lighting was present in the close proximity of a Li-Fi unit. However, it is strongly recommended that the issues of interference be checked and controlled for in other applications, where their sources might be present. Secondly, the two levels of vibration (On & Off) were controlled by oscillating the normal site operation between the functions of on and off. Future research can perhaps measure and control this vibration using a vibration bed to evaluate and characterise it against the connection speed.

Conclusions

The study presented in this article was aimed at reducing high failures due to connection issues using a specific IR-based Li-Fi transceiver in the logistics industry. The failures due to connection issues were completely eliminated with the implementation of a robust solution. Alignment and distance between the two transceivers were the most critical factors affecting the connection speed. The Li-Fi surface area to send and receive signal proved to be critical for delivering an effective solution that can deal with higher positional variation. All these factors were successfully identified, characterised and optimised using the Six-Sigma methodology. Li-Fi is an emergent wireless communication technology that has found application in a wide variety of industries. Once the connection speed issue was resolved, Li-Fi performed exceptionally well in providing an interference-free and secure connection between moving objects.

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Striving for smart mobility in Morocco: a case of lanes designated to heavy goods vehicles in Casablanca

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Ali Agoumi

ABSTRACT

This article highlights the need to rethink how to manage mobility in Morocco more intelligently, given that it is a major pillar of economic competitiveness. Smart mobility based on Intelligent Transport Systems (ITS) allows to improve and ensure the optimal use of existing infrastructure before embarking on heavy and irreversible infrastructure projects. The case regarding the separation of the urban traffic and the Heavy Goods Vehicles (HGV) traffic circulating between Casablanca Port and Zenata Dry Port is a relevant example where smart mobility could provide efficient solutions without building costly tunnels. A dynamic simulation was made using the Aimsun software to quantify the relevance of the proposed lane designated to HGV in the existing road. This simulation allows to visualise congestion sections and quantify the circulation of vehicles and pedestrians. The article presents defined functions and characteristics of the Advanced Traffic Management (ATM) to ensure the optimal operation and efficient setting of the simulation. All appliances, hardware, and sensors that will be set up on-site will help to improve traffic safety, traffic flow, traffic information, and reduce congestion and pollution. This case study illustrates the complexity of managing the flow of goods in cities and suggests how to solve this type of problems using smart mobility. This research proposes reserving a special lane for HGV. ITS will help this cost-optimal alternative, will promote the urban framework of the coastal road, and contribute to sustainable mobility in Casablanca.

KEY WORDS

sustainable mobility, smart mobility, intelligent transport systems, advanced traffic management, heavy goods vehicles

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Introduction

Managing mobility of people and goods in large cities is a thorny issue. The growing demand for travel of urban populations put pressure on transport infrastructure. Major Moroccan cities are no exception to the struggle, aiming to respond to the challenges of accelerating urbanisation and increased mobility demands. This will inevitably prevent them from turning into smart cities.

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Smart cities can be identified by six closely-linked levers: smart economy, smart mobility, a smart environment, smart residents, a smart lifestyle and smart administration (Giffinger et al., 2007).

Therefore, a “smart city” (Bashynska & Dyskina, 2018; Winkowska et al., 2019) is inseparable from “smart mobility”. The Fourth Industrial Revolution and the digital transition impelled to rethink mobility management: the design and construction of road infrastructures, new services for “connected mobility” without excessive waiting or congestion at interconnections, and functional and economical solutions for operation and maintenance (intelligent sensors, user information solutions, intelligent transport infrastructure, and systems).

The term “smart” certainly alludes to better use of technologies, but “smart mobility” is also defined as “a set of coordinated actions intended to improve the efficiency, effectiveness and environmental sustainability of cities” (Benevolo et al., 2016). The term “mobility” highlights the preponderance of humans over infrastructure and vehicles.

Current solutions for traffic congestion consist of fitting and widening infrastructure, which only encourages more trips and results in even more critical consequences. Even intelligent transport systems are helpless beyond certain traffic density.

The concept of dynamic lane management opens up new perspectives. Its objective is to manage and optimise road traffic in a variable manner, in space and time. Generally speaking, it is “Advanced Traffic Management”, “Active Traffic Management” (ATM), or “Managed Lanes” (ML).

In Casablanca, the traffic problem is one of the major challenges, which must be addressed irrespective of the choice by decision-makers to implement a “smart city” solution. An efficiency gain in terms of circulation and mobility could lead to significant savings. However, it appears that conventional traffic management would not sustainably absorb the consequences of congestion during peak hours. Traffic congestion inevitably leads to the deterioration of the urban framework and road safety conditions and harms the city’s competitiveness.

Growing HGV flows from or to the Casablanca Port intensify congestion, result in roadway degradation and other negative impacts, such as pollution (noise, air, visual). Moreover, they contribute to the consumption of public spaces and the mortality of alternative mode users. At the same time, industrial and commercial blocks in the city centre with storage facilities generate a high demand for transport and parking.

Consequently, the effort to divert HGV flows from the city centre becomes a major urban challenge. The optimisation of logistics for the delivery of goods is vitally important for the competitiveness and attractiveness of the city, the improvement of the quality of life, accessibility, and road safety.

The mega-project “Wessal Casablanca Port” includes the development of a 17 km seaway connecting the port of Casablanca with Zenata Multi-Flow Logistics Zone (MFLZ). This project aims to enhance and develop the historic area of the Casablanca Port for tourism, with a view to relieve the main urban axes, improve traffic conditions, and streamline the flow of goods.

The strategic position of the dry port of Zenata MFLZ will be reinforced upon the completion of an efficient connection road with the Casablanca Port, which is the main traffic generator in the city. Zenata MFLZ will take over a large part of the cargo from the current port, which handled 30 million tonnes in 2019 and concentrates almost 20% of the import/export traffic of Morocco (METLE, 2018).

This case study concerns the connection of the Casablanca Port and Zenata MFLZ by 5 km long coastal road (Fig. 1).

The development of this project must meet the following requirements:

- an optimised impact on the expropriation and the networks;
- design compatible with the adjacent cornice Ain Sebaa project from an urban and functional point of view;
- flow and protection of pedestrians heading towards the beach;
- separation of port traffic and urban traffic;
- sufficient capacity on the current section of lanes reserved for HGV;
- maintained operation in the event of accidents in the lanes reserved for HGV;
- secure traffic at intersections;
- travel time promoting the competitiveness of the logistics area;
- flow of vehicles and improvement of capacity on highways;
- flow and unrestricted management of traffic during development works;
- limited equipment maintenance;
- remaining within the project budget.

This article reflects on the development of the road dedicated to HGV, the first of its kind in Morocco. The project aims to alleviate the discomfort caused by trucks in the urban road network of Casa-

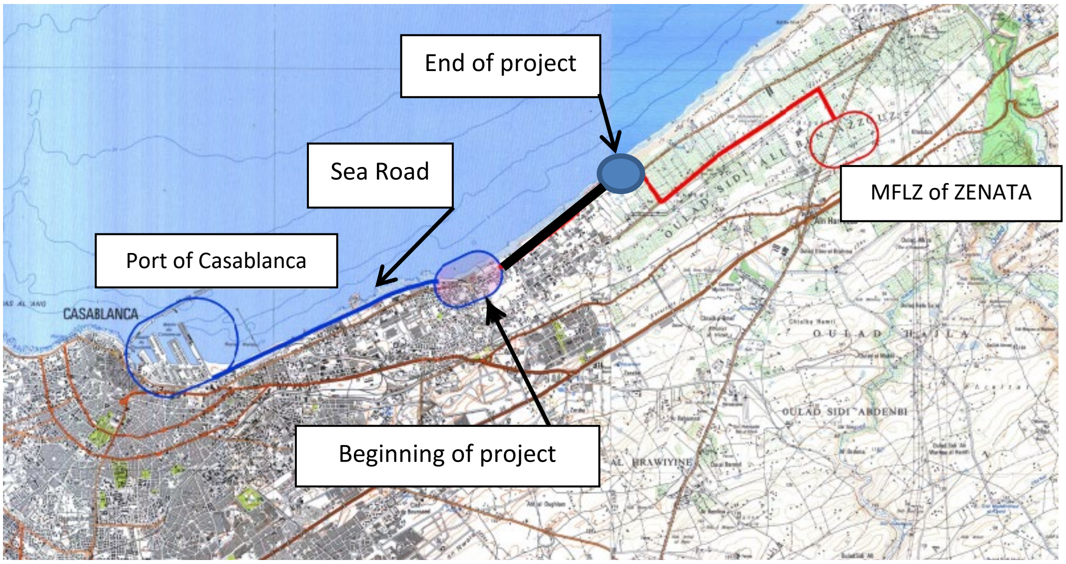

Fig. 1. Location of the project connecting the Casablanca Port and Zenata MFLZ
Source: Map of Morocco – topographic map of Casablanca 1/50000.

blanca. This research is an ideal opportunity to reflect on the introduction of ITS to ensure the optimal use, especially at intersections and pedestrian crossings of urban roads in Morocco.

1. Literature review

Next, the article reviews the international experience concerning designated HGV roads, then initiatives and strategies concerning HGV in Morocco, and finally, presents an analysis of the current situation of mobility in Casablanca.

1.1. Republic of Mauritius

To streamline port traffic between the Red Sea and the Jin Fei industrial area and increase the existing motorway capacity, a third lane dedicated to trucks was built in July 2019, extending 3.1 km and having the width of 4 m on each side. The traffic saturation in the North region and the separation of traffic from container ships will allow the birth of a smart city (Maurice Actu, 2019).

Several innovations have been included in the project, such as demarcated lanes, traffic signs conforming to the Vienna Convention to improve road safety, and Light-Emitting Diode (LED) lighting to offer better brightness and visibility and improve energy efficiency (Maurice Actu, 2019).

However, the buy-in of various stakeholders was not ensured during the design phase, which resulted in the change to the initial route. The third lane had to be built using red asphalt, and 200 trees were felled without replanting (Maurice Actu, 2019).

1.2. State of Georgia in the USA

The State of Georgia has decided to deploy major means to ease traffic on its motorways, which are particularly heavily loaded with HGV. Georgia has decided on the record investment of more than USD 2 billion and a construction site planned for at least four years to create one or two additional lanes on certain portions of motorways (Masquelier, 2018).

These new lanes will be exclusive for HGV and will be separated from the rest of the traffic by a theoretically insurmountable barrier. They will link Atlanta suburbs to the rapidly developing Macon City, about 40 miles away. This project is interesting from multiple points of view.

The new lanes will solve the congestion problem, allow to transport goods more quickly and easily, and make transport safer in general. The routes will be fitted with sensors to inform truck drivers in real-time regarding possible traffic jams and slowdowns so that they can modify their routes if possible (Masquelier, 2018).

1.3. Germany

In 2019, Germany started a three-year project that equipped 10 km of motorways with energy supply by overhead catenary in a lane dedicated to hybrid trucks, i.e., the e-highway. The section between Weiterstadt and the Langen / Mörfelden exit is called the ELISA Project. This motorway segment receives

135000 vehicles daily, 10% of which are HGV (Taberlet, 2019).

This infrastructure is one of the neutral goods transport solutions developed in the country. According to Siemens, EUR 20 000 in fuel savings can be achieved for a 40-tonne truck travelling at 80 km/h using this system over 100 000 km (Taberlet, 2019).

1.4. France

In France, the road haulage industry accounts for more than EUR 53 billion with an annual turnover of about 280 billion tkm. The French authorities, favouring the transport of people above all, seem cautious to invest in the transport of goods, in particular, semi-autonomous vehicles and reserved traffic lanes. France is currently constructing dedicated lanes, but they will firstly be reserved for buses and taxis before carpool (Masquelier, 2018).

Since 2016, several manufacturers of trucks, such as DAF, IVECO, and SCANIA, have joined forces to think about new solutions for the transport of goods to optimise overall costs, improve the safety of truck drivers and motorists, and reduce CO2 emissions (Masquelier, 2018).

The companies created a truck platooning project (a convoy of semi-autonomous trucks) TOGETHER, which should be operational from 2021. Once real road traffic needs are established for each participant, equipment manufacturers will quantify and budget this new system for transporting goods. From 2021, concrete tests are planned, probably in the Netherlands. They can already rely on Germany's encouraging results in terms of platooning. For several months now, DB SCHENKER and MAN TRUCK & BUS have been testing the solution in Bavaria (Masquelier, 2018).

1.5. Morocco

In 2014, the National Sustainable Development Strategy 2030 (SNDD 2030) identified the transport sector as the third energy consumer in Morocco. It accounts for 16% of total emissions and 28% of emissions from energy. Sustainable mobility is defined as "a transport policy which seeks to reconcile accessibility, economic progress, and the reduction of the environmental impacts of the selected transport systems" (SEDD, 2017). The transport of goods is also concerned with ambitions to optimise existing networks and improve nearby exchange platforms and New Technologies of Information and Communication (NTIC), allowing efficient transfers between different modes of transport.

Morocco is the first country to have initiated an adaptation of the global macro-roadmap for the transformation of transport based on the Paris Process on Mobility and Climate (PPMC). The 2018 Moroccan Roadmap, which aims to support national strategies and, more particularly, the SNDD 2030, recommends the creation of vertically and horizontally integrated, sustainable industrial zones close to consumption and connected to mass transportation modes. Defragmented and shortened supply chains reduce the need for transport and eliminate unnecessary trips.

Over the past decade, Morocco has seen significant progress and reforms in the areas of the environment, sustainable development, and the fight against climate change. Several sectoral strategies, including transport and logistics, integrate these environmental dimensions. The economic stakes are high as the cost of air pollution in Morocco accounts for more than 10 Md DH (1% of GDP) (METLE, 2018).

Morocco is implementing an integrated national strategy for the development of the logistics sector by 2030 with clear and quantified macro-economic, urban, and environmental objectives. Since sustainable development is at the heart of this strategy, its objectives contribute to a reduction of around 35% in CO2 emissions resulting from the transport of goods by road (METL, 2017).

To achieve these objectives, pooling flows of goods has been considered as a primary solution. The creation of 3000 ha of logistics platforms by 2030 is among the main levers for reducing delivery costs and the carbon footprint of the import/export supply chain, thereby improving the quality of life, accessibility, and competitiveness of urban communities (AMDL, 2016).

Thus, the dry port of Zenata will divert more than 13000 HGV per day by 2025 from the city centre of Casablanca (ANP, 2019). This solution will:

- relieve the key axes of the city and improve road safety by diverting the port traffic, which currently uses the main roads of Casablanca, particularly the coastal road;
- shorten HGV journeys and travel time;
- improve working conditions and transport of goods and, consequently, the competitiveness of transport companies.

1.6. Mobilise Your City

One hundred metropolises are committed to "Mobilise Your City (MYC)" — an initiative aimed at a proactive transition and a deep cultural and organisational transformation of mobility and logistic activities to make cities more inclusive and reduce greenhouse gas (GHG) emissions. This initiative builds on collective intelligence networks and existing planning practices based on principles of integration, participation, and evaluation (MYC, 2019).

Made of a coalition of international partners (development agencies, urban transportation planning agencies, non-governmental organisations and development banks), MYC offers a methodological framework, capacity building, technical assistance and facilitates access to financing at the local and national levels. The initiative will develop an international benchmark platform for sharing best practices and technical and academic expertise in planning sustainable urban mobility.

Morocco was among the first countries to have embarked on the MYC initiative during the COP22 in Marrakech in 2016. Efforts to implement mobility planning in 26 municipalities and the sustainable development approach, stemming from the MYC project, had the following objectives:

- improve the quality of life and the economic attractiveness of the city;
- improve transport systems and propose alternative solutions to individual vehicles;
- adopt solutions that are more capable of saving space and reducing carbon footprint, and are affordable and adapted to the needs of the inhabitants;
- set up a Sustainable Urban Mobility Plan (SUMP).

In 2019, Casablanca was selected by IEEE, a prestigious American scientific organisation, to be part of the IEEE Smart Cities Initiative. The city was recognised for innovative projects aimed at the transformation to a smart city and intentions to invest in the human and financial capital of the city.

1.7. Casablanca's Urban Mobility Plan

Casablanca's Urban Mobility Plan (UMP), drawn up between 2004 and 2008, is a planning document that defines a coherent organisation scheme for the mobility of people and goods within the Perimeter of Urban Transport for 15 years. It includes the definition of a frame of reference and objectives broken down into 25 actions that guide elected officials in their decisions.

Aiming to tackle economic, urban, and environmental challenges the Casablanca's UMP considered the following trend scenario (Ministry of the Interior, 2004):

- the energy consumption: MAD 4.2 billion in 2004 compared to MAD 9 billion in 2019;
- the cost of congestion: MAD 114 million in 2004 against MAD 3.4 billion in 2019;
- the cost of pollution: MAD 319 million in 2004 against MAD 1 billion in 2019.

To address these challenges, the priority actions recommended in the Casablanca's UMP include the creation of logistics lanes for HGV on a regional scale. But this approach, which aimed to resolve the problems by a mode of transport, has its limits. Mobility demands must be the primary focus rather than transport infrastructure as an input.

2. Research methods

Based on automatic counting results established by a permanent post, the average annual daily traffic on the coastal road is 21 000 vehicles (DR, 2018). A metering campaign quantitatively and qualitatively determined a load of directional traffic at crossroads and in the section during the rush hour. The maximum peak hourly traffic at the section is around 3300 vehicles in both directions, 10% of which are 13-m-long HGV.

The strongest hypothesis of the National Ports Agency (ANP) considers that 100% of container HGV (3200 HGV) and 100% of non-container HGV from port activity (5600 HGV) will pass through the northern service in both directions daily. The peak hourly traffic is 1100 HGV (36% of 13-m-long HGV and 64% of 17-m-long HGV).

To quantify the impact of the proposed lane dedicated to HGV, a dynamic simulation was carried out using the Aimsun software. This simulation allows visualising the circulation of vehicles and pedestrians at crossings. The above-described traffic data was used to generate vehicle traffic on the main road and secondary roads.

Several replications were launched to obtain an average per hour. Each replication generates traffic randomly over time while respecting the origin/destination matrix.

Thus, each replication has variations in traffic, making it possible to observe different traffic conditions (local congestion, repetitive calls on secondary axes, absence of pedestrian calls).

3. Research results

3.1. Analysis and proposal for the development of a lane reserved for HGV

Possible options

Six variants can be considered:

- Variant 1: a road in 2x3 lanes for mixed HGV and urban traffic (Fig. 2).
- Variant 2: dedicated corridor for HGV, partial separation of traffic
  - Sub-Variant 2.1: dedicated central corridor for HGV in 2x2 lanes (Fig. 3).
  - Sub-Variant 2.2: dedicated central corridor for HGV in 2x1 lanes (Fig. 4).
  - Sub-Variant 2.3: dedicated corridor for HGV in 2x1 lanes (Fig. 5).
  - Sub-Variant 2.4: two dedicated bilateral ways for HGV (Fig. 6).
- Variant 3: dedicated corridor for HGV in 2x2 lanes and uneven junctions, total separation of traffic (Fig. 7).

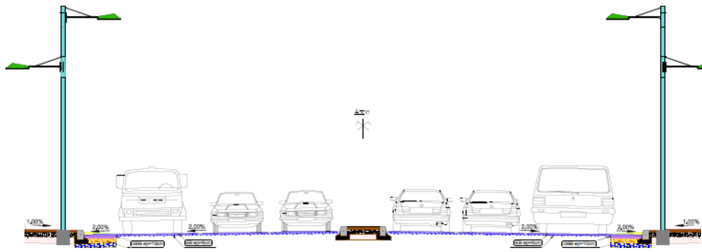

Fig. 2. Cross-type profile of Variant 1

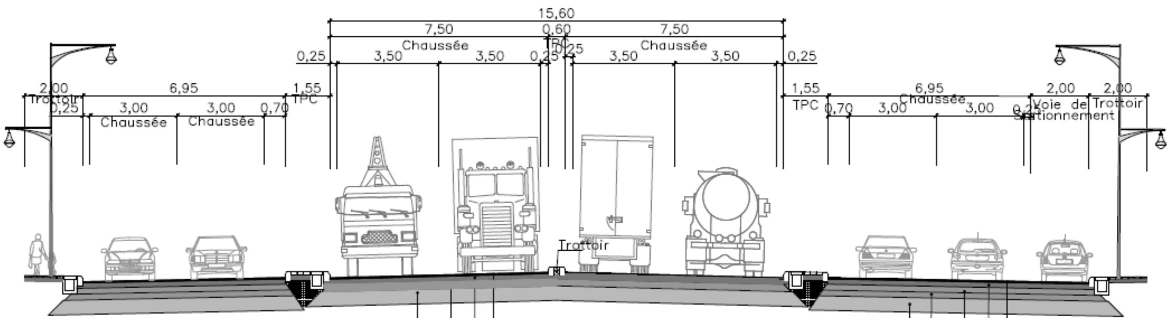

Fig. 3. Cross-type profile of Sub-Variant 2.1

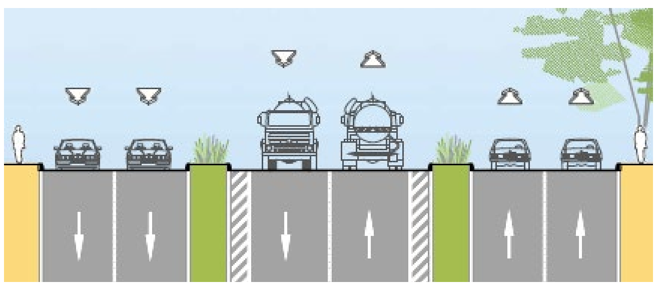

Fig. 4. Cross-type profile of Sub-Variant 2.2

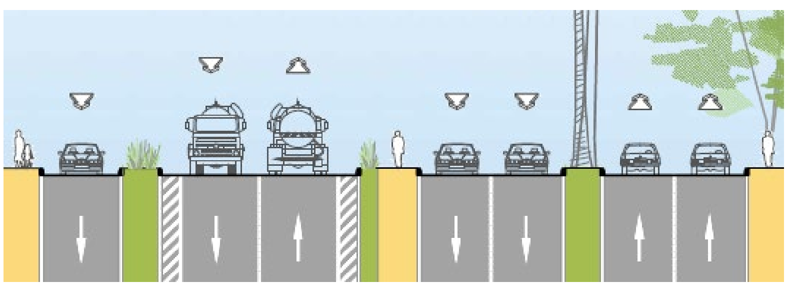

Fig. 5. Cross-type profile of Sub-Variant 2.3

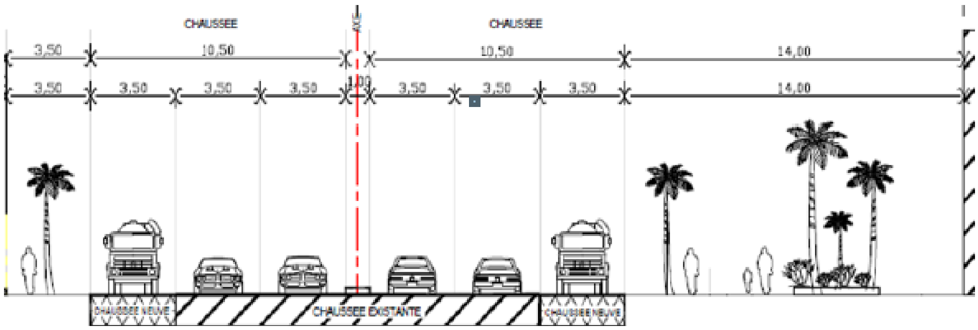

Fig. 6. Cross-type profile of Sub-Variant 2.4

Fig. 7. Cross-type profile of Variant 3

Tab. 1. Multi-criteria analysis

Variants Analysis criteria	Variant 1	Sub-Variant 2.1	Sub-Variant 2.2	Sub-Variant 2.3	Sub-Variant 2.4	Variant 3
Land impact	++	-	+	+	+	--
Network's impact	++	-	+	+	+	--
Compatibility with the Corniche	++	-	+	--	-	--
Landscaping	++	--	+	-	-	--
Pedestrian flow	+	--	++	+	-	--
Pedestrian safety	-	--	+	--	-	-
Separation of HGV traffic from urban traffic	--	+	+	+	+	++
Reduction of conflict points	--	+	+	--	-	++
HGV exit/entry possibility via intermediate intersections	++	+	+	-	+	--
Travel time	--	+	+	+	+	++
Traffic during works	+	-	+	+	-	--
Cost/completion time	++	-	+	+	-	--

Legend: (--) Very negative / (-) Medium to negative / (+) Positive / (++) Very positive

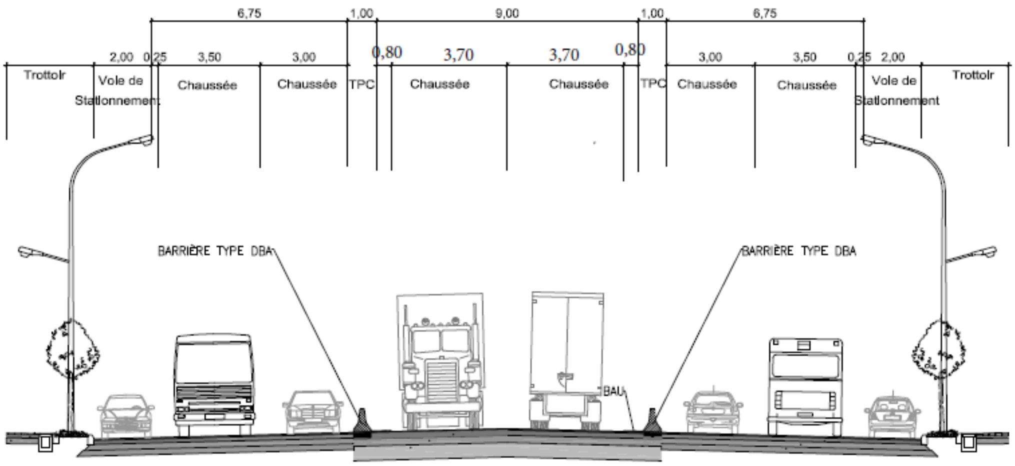

Fig. 8. Cross-type profile recommended of Sub-Variant 2.2

Multi-criteria analysis

Based on the defined requirements in the introduction, six proposed variants were evaluated to find the best alternative (Tab. 1).

Recommended alternative

Considering the multi-criteria analysis, Sub-Variant 2.2 can be recommended. Its feasibility was subsequently studied. The cross-type profile (Fig. 1) of this variant is as follows:

- 2x2 lanes of urban traffic at the lateral level and the 3rd turn left lane at the crossroads;
- central corridor dedicated to HGV in 2x1 lanes, 9 m wide:
- a separation between the two corridors by movable double concrete partitions in the event of an accident;
- support measures in terms of detection and traffic management.

3.2. Checking the feasibility of the planned HGV lane

Verification of the proposed lane width

Figs. 9 & 10 show that the proposition of the 9 m width for the two bidirectional lanes dedicated to HGV means the operation in a degraded mode in the event of a truck failure on the lane. Measures can be used in the event of a truck breakdown, such as mov-

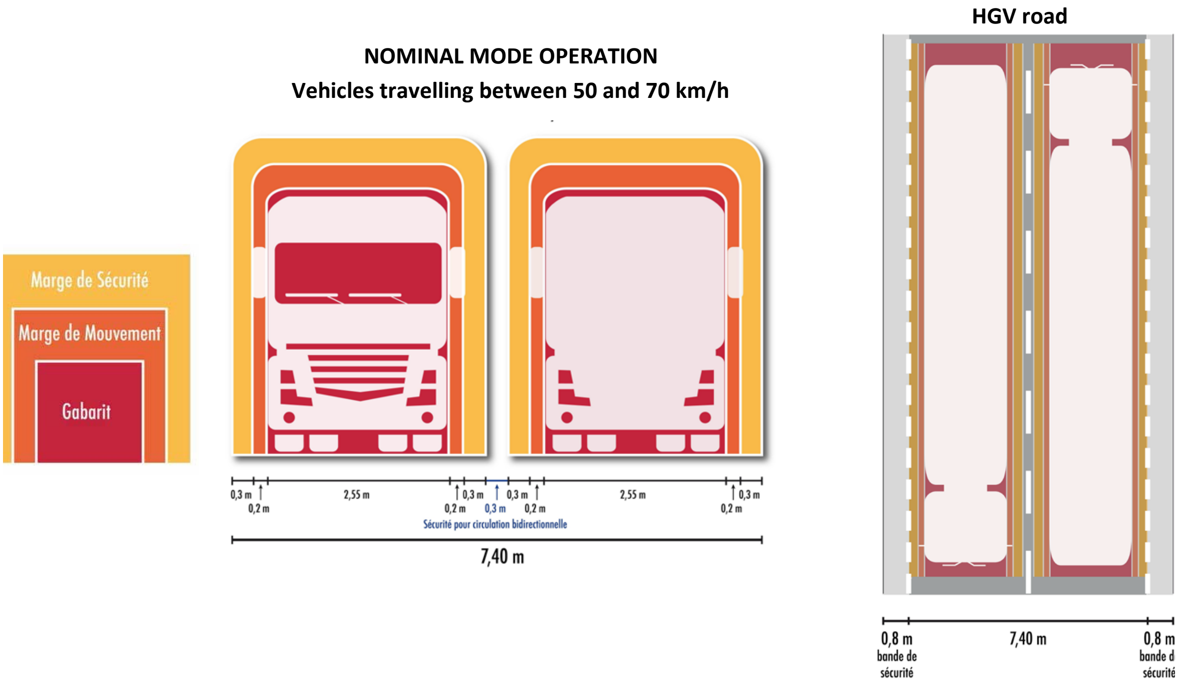

Fig. 9. Checking the gauge of dedicated traffic lanes for HGV in nominal mode operation

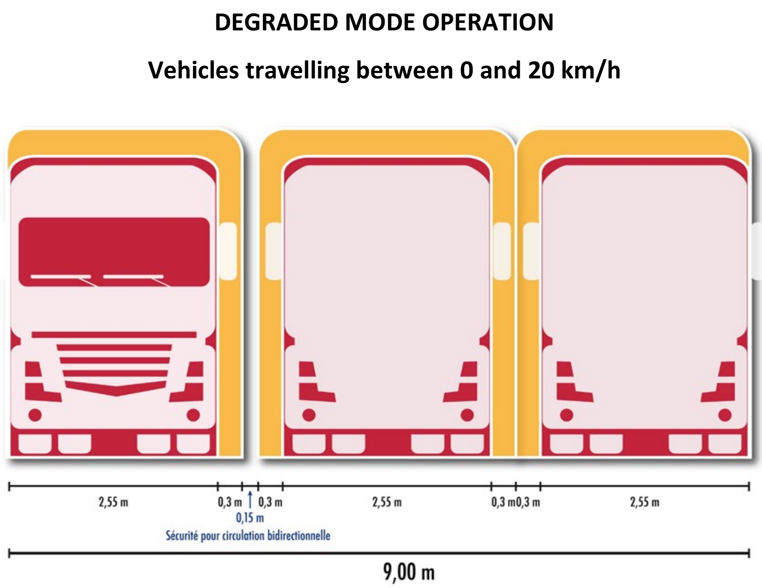

Fig. 10. Checking the gauge of dedicated traffic lanes for HGV in degraded mode operation

able double concrete partitions used to clear HGV through side lanes in the event of a serious accident in the HGV lane.

Implementation of the simulation

Intersections regulated by traffic lights are programmed in the Aimsun software as follows:

- cycle time of 80 seconds;
- keeping the main axis green (at least 45 seconds of green to clear the 550 HGV/h per direction);
- turn left and secondary axes phases on-call (8 seconds of green for each phase).

Sensors are placed on the turn-left lane and secondary axes to detect the presence of a car and leave the rest to the main phase.

The Aimsun software has a "yellow box" function for traffic intersections. When this function is activated on the crossroads, vehicles do not enter in the case of a risk of lifts and blocking. Vehicles wait at the light until the intersection empties. To reproduce the effect of the "yellow box", the saturation loop system and early closing of lanes at stop lines are to be expected (Fig. 11 and Fig. 13).

Pedestrians at the crossroads can cross during turn-left phases and the operation of secondary axes. Pedestrians on secondary axes can cross during the main phase. Pedestrian detection devices will be used for these crossings to reduce the waiting time for pedestrians if no vehicles are approaching the crossroads.

To manage pedestrian crossings on call, a dedicated facility will be created for pedestrian traffic. When a pedestrian is detected, a call is made, and the car/HGV phase turns red after 29 seconds so as not to

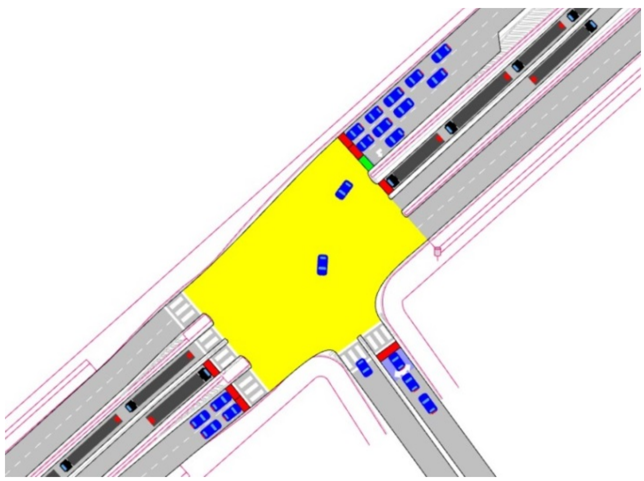

Fig. 11. Crossroad operation with "Don't block the box" mode

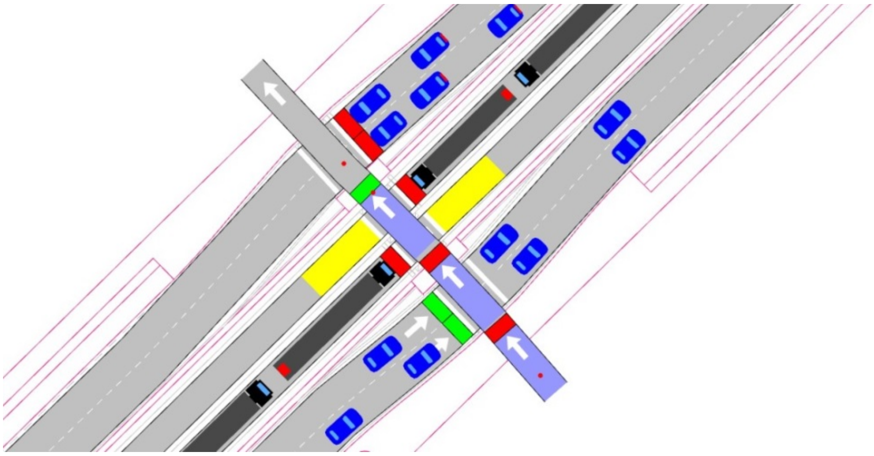

Fig. 12. Pedestrian crossings with “don’t block the box” mode

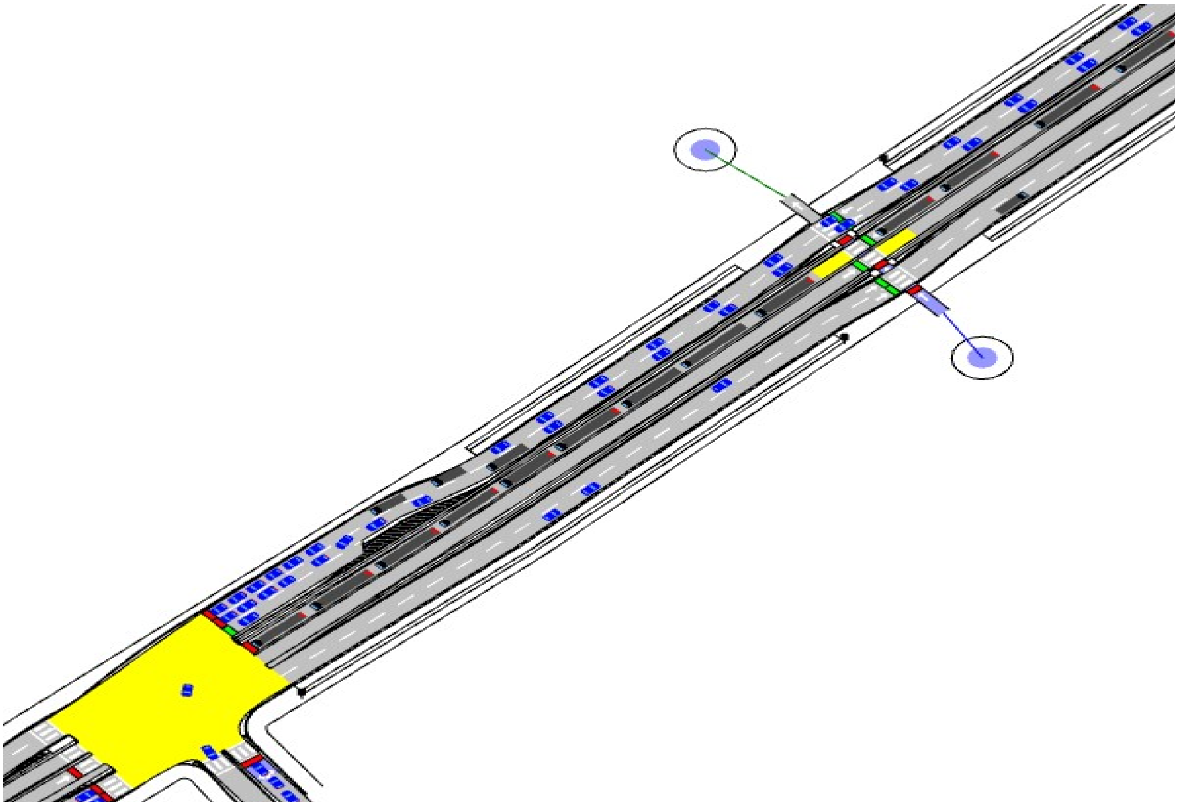

Fig. 13. Simultaneous operation of crossroads and pedestrian crossings with “don’t block the box” mode

constrain the flow of vehicles. The operation of pedestrian crossings on call impedes the creation of a green wave on the entire road.

To optimise the operation of pedestrian crossings transversely, each pedestrian signal opens in the offset to limit the times of red car/HGV (pedestrian green wave principle).

A “yellow box” is placed downstream of the pedestrian crossing (Fig. 12). This function is activated in order not to have a car/HGV blocking the pedestrian crossing. Trucks do not cross the pedestrian crossing if there is insufficient space for it to stop. The blue areas on the pedestrian path are detectors that activate the pedestrian green when a presence is detected.

4. Discussion of the results

4.1. Simulation Analysis

HGV traffic on a dedicated central site

In the simulation, all HGV arrive at their destination without too much waiting due to congestion. The average journey time is 12 min over the entire section. Their total downtime is 3 min and 40 sec. The average speed is 25 km/h (Fig. 14).

Vehicle traffic on the sideways

Vehicles (825 vehicle/lane/direction/hour) benefit from the same green time as HGV (1475 vehicle/lane/direction/hour) although their number is less. Therefore, no problem arises with the queue.

Cars travel 5 km in 9 min, which means the average speed of 32 km/h (Fig. 15).

Vehicles coming from the secondary axis of an intersection regularly pass to the second cycle. This intersection as a resting point on the main one operates cyclically due to the permanent calls from the secondary axis. Vehicles wait an average of 75 seconds to pass the lights (green time amounting to 10 seconds).

Pedestrian flow

Fifteen pedestrian crossings in the section are managed with a pedestrian pushbutton and the thermal detection system. A detected pedestrian is given 29 seconds after the detection to leave a minimum of green time for HGV in the dedicated site. On average, a pedestrian takes 54 seconds to cross the entire road (including detection time) with an average speed of 5 km/h (Fig. 16).

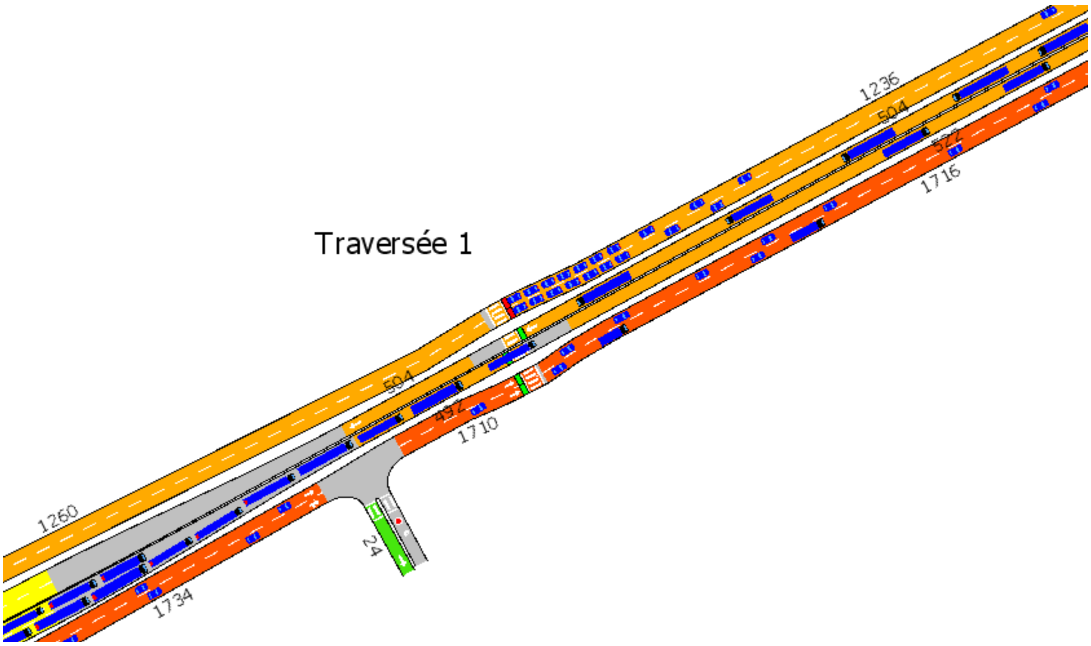

Fig. 14. Calculation and verification of hourly flow rates in lateral lanes and dedicated lanes

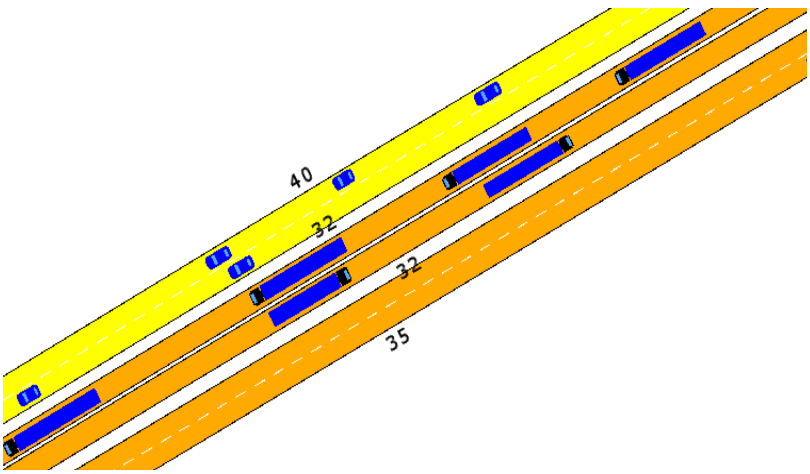

Fig. 15. Average speed in the lateral road and HGV lanes

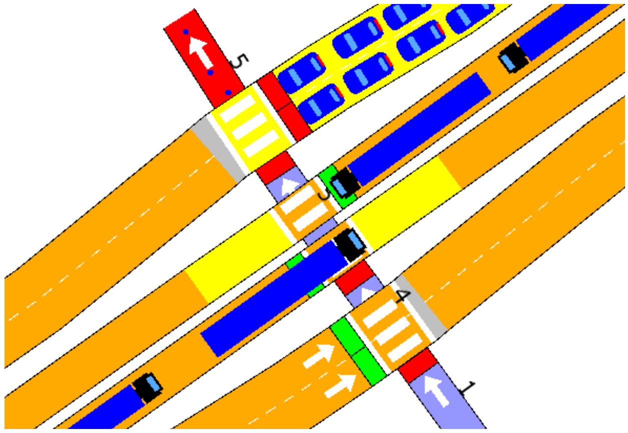

Fig. 16. Average speed at pedestrian crossings

4.2. ITS Criteria

To ensure the optimal simulated operation at the Aimsun software level, the equipment of the vehicle and pedestrian detection system and ATM must constitute an ITS and have the following functions:

Diagram of the overall functioning of the ATM system

The diagram below summarises the overall operation of the integrated traffic operating system allowing ATM with prioritisation of HGV flow, detection and securing of pedestrian crossings, intelligent management of traffic lights, information for users through Variable Message Panels (VMP) and data acquisition and monitoring using the Internet (Fig. 17).

The adaptive and intelligent traffic light controller

It is an automated system dedicated to adaptive management and intelligent regulation of road traffic without a central control having the following specific characteristics:

- history of traffic data, analysis, optimisation and evaluation of the effectiveness of the dynamic control system;
- recognition of the absence of a vehicle at the intersection to avoid unnecessary priority-giving;
- processing of information from various traffic detectors;
- compatibility with DIASER and OCIT 2.0 communication protocols;

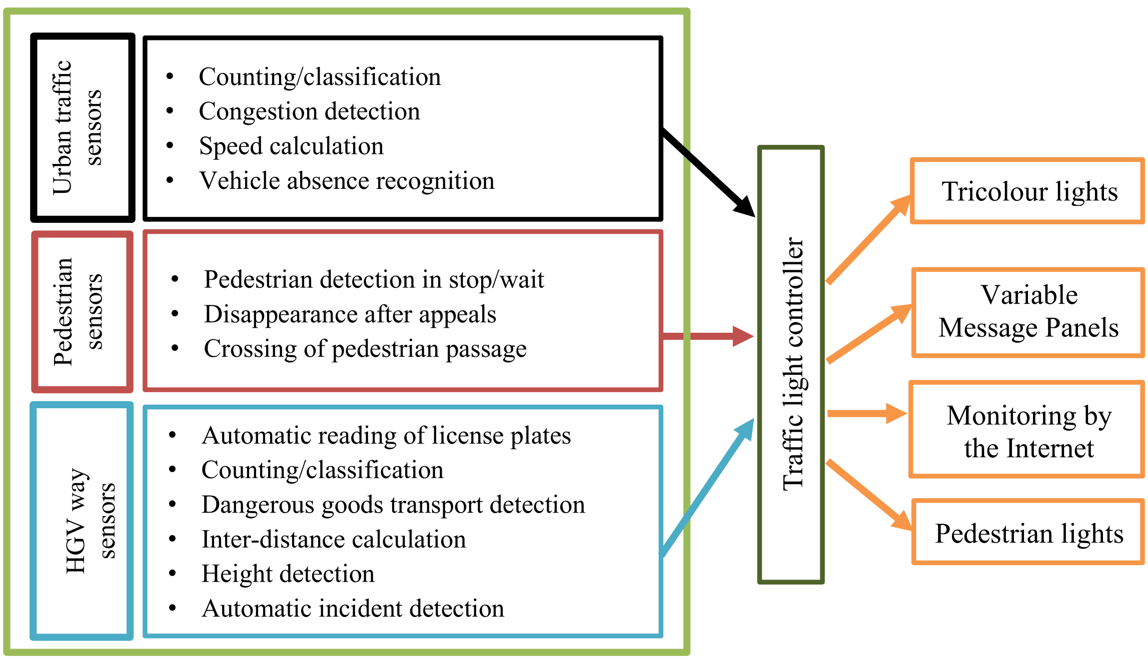

Fig. 17. Overall functioning of the ATM system

- equipped with SIL3 (Safety Integrity Level): redundancy of controls;
- complies with the requirements of EN12675 and EN50556 standards;
- programmable with third-party software LISA + and VS-PLUS;
- capable of controlling traffic lights in different voltages (230VAC / 110VAC) with bulbs or LEDs, 40VAC for LEDs, 24VDC (compatible with LEDs 1W, 10VAC);
- possibility of attenuation mode at nightfall with 42VAC dimming module;
- the possibility of manual control;
- priority configuration for firefighters/police/ emergencies;
- equipped with programming and maintenance software;
- visualisation module system by the website.

Thermal detection system

It is a thermal imaging camera for vehicles and pedestrians with the following characteristics:

- detection of the lane saturation;
- Automatic Incident Detection (AID) on the HGV lane for traffic diversion through cross-arrow aspects;
- detection of pedestrians waiting and crossing;
- dynamic micro regulation of tricolour lights cycle times;
- "don't block the box" flow and saturation control;
- vehicle counting and classification;
- access height detection;
- reading Dangerous Goods Transport (DGT) plates;
- calculation of HGV speed through virtual loops (If V> Vmax: the light turns red);
- automatic Reading of License Plates (ARLP) by day and by night;
- all-in-one sensor (infrared and Complementary Metal Oxide Semiconductor (CMOS) "very high sensitivity");
- 24/7 detection in various weather conditions, without the need for additional lighting;
- low maintenance;
- IP connectivity and configuration via secure Wi-Fi / 3G connection;
- eight vehicles or pedestrian presence zones;
- video stream visible in Haut Definition Protocol (HD) and Real-Time Streaming Protocol (RTSP);
- countdown of the waiting time before going green;
- management of Variable Message Panels (VMP) and cross-arrow aspects.

Polycarbonate signal lanterns

The polycarbonate signal lanterns must have the following characteristics:

- led technology;
- optically attractive modern design;
- slim design, appropriate for historic urban areas;
- available in different colours and colour combinations;
- can be mounted vertically or horizontally;
- available in ø 100/210/300 mm;
- anti-vandalism.

LED modules

LED modules must have the following characteristics:

- no visible LED point — the central light source;
- higher anti-ghost performance (class 5);
- lower energy consumption and brilliant light output;
- products traceable by serial number;
- custom masks that can display any symbol;
- life cycle > 5 years;
- optimised thermal concept, reducing degradation to a minimum;
- automatic light compensation in case of diode failure;
- degraded mode functions available in 42V;
- compliant with DIN VDE 0832 standard.

Pedestrian pushbutton

Pedestrian pushbuttons must have the following characteristics:

- modular design allowing the adaptation to all types of intersections;
- no moving parts which could be deactivated with toothpicks, gum;
- anti-vandalism (solid body and integrated metal-core); laterally tactile symbols appeal to describe the passage for the visually impaired;
- location of the pushbutton, thanks to the acoustic and optical position signal (LED ring);
- integrated acoustic units;
- meet all the requirements of the current directives and regulations (RILSA, DIN 32981, DIN VDE 0832, EN 50293).

Environmental sensor

Environmental sensors should allow for the following:

- measurement of gases (NO2, O3, CO, CO2, VOC);
- measurement of polluting fine particles (PM1, PM2.5, PM10);
- measurement of humidity, temperature, and pressure;
- noise measurement.

Weighing at the current speed

Weighing-in-motion systems with dynamic weighing sensors help to quickly detect vehicles and axle weights for safer roads and better traffic management.

Conclusions

The installation of 15 secure pedestrian crossings throughout the 5 km of the project, in addition to a pedestrian crossing on each of the five main intersections, has made it possible to reduce HGV speed to manage traffic and ensure the maximum protection of pedestrians. Besides, with the help of ITS, several issues related to traffic regulation and flow have been resolved. The dynamic and adaptive management of traffic lights has, therefore, made it possible to reduce ways dedicated to HGV while minimising journey time.

The use of ITS will allow the registration of traffic data, the collection of information about special events, and the management of system efficiency for real-time. The innovations and intelligent systems made it possible for HGV to bypass the downtown of Casablanca with a significant gain in terms of business competitiveness and a substantial positive impact on the quality of life of citizens and the urban environment.

Future research will focus on the national level in Morocco, establishing a barometer to draw up an inventory of the dynamics of Moroccan cities and their existing and future smart city strategies. This research will allow tracing the roadmap for accelerating the sustainable transition and the transformation of Moroccan cities into smart cities. The barometer will provide an analysis of the data collected from a pre-established sample. Three conceptual models will be considered: the three components of the smart city by Nam and Pardo (2011); the six dimensions of the smart city by Giffinger et al. (2007); and ISO 37120: 2014.

The barometer will have to deal with four essential components:

- The first part will concern the understanding and apprehension of the concept of the smart city by various city stakeholders. It will identify the main perceptions associated with the emergence of the smart city and measures the importance given to technological, human and institutional factors. Finally, it will present a self-assessment established by the cities themselves to monitor the progress in the implementation of a smart city approach.
- The second part will explore the strategic axes developed within cities. It will present the prerequisites essential for strengthening a local strategy oriented towards a smart city approach. It will then highlight the main themes under development, the values conveyed, and the formalisation actions carried out to support smart city projects.
- The third part will deal with the implementation and monitoring of smart city projects. It will focus on the level of involvement of various actors and current or planned means of financing, and initiatives to strengthen the dynamics of the various stakeholders (public and private actors as well as citizens). Finally, it will identify the benefits generated as well as the obstacles encountered in the implementation of smart city projects.
- Finally, the last section will indicate the monitoring and control procedures as well as the obstacles that cities may encounter in the implementation and development of smart and sustainable city projects and the recommendations to overcome them.

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Heuristic comparative assessment of non-conventional warehouse designs

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ABSTRACT

In the unit-load warehouse (UW) design, the aisle design problem dealing with storage space layout is the first among the three main problems. Several conventional and non-conventional designs have been proposed in the literature. In general, the assessment of UW designs is commonly carried out using analytical approaches. However, such an approach may be inadequate due to assumptions or approximations, making results unrealistic. Aiming to bridge this gap, this research develops an assessment framework that employs the FlexSim software for simulating the conventional, Flying-V and Fishbone designs based on a real case from a Philippine manufacturing company. Using a computer simulation, this research investigates factors not yet tractable with present analytical methods. The factors employed for the comparative assessment are "picking run-time", "travel distance", and "capacity". The results suggest that the Fishbone design provides the most advantage compared to the Flying-V and other conventional designs. With the proposed Fishbone design, the company is expected to save, on average, 52.39% of picking run-time, 32.25% travel distance, and increase storage capacity by 7.5%. The research findings are compared to previous studies based on analytical approaches.

KEY WORDS
warehouse design, aisle design, production layout, Flying-V design, Fishbone design

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Introduction

Several component subsystems exist in distribution centres (DCs), which are typically categorised based on processes. These subsystems include receiving, storage, order picking, and shipping. The pallet storage area is the most common building block of these systems. It consists of storage racks, aisles between them, and one or more pickup and deposit (P&D) points (Gue & Meller, 2009), commonly called a "warehouse". Most space in a DC is usually allocated

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for the warehouse. Almost all products are received and stored in pallet quantities in this area. Warehousing does not necessarily add value to the product; however, it is undoubtedly essential in operations (Feng et al., 2018), which in recent years has drawn research interest to the topic, especially in logistics research.

Unit-load warehouse (UW) designs were among the highly explored logistics research topics (Feng et al., 2018). UWs are used to store items — typically, pallets — that can be stowed or retrieved in a single trip and usually handle standardised cargo types. According to Gue and Meller (2009), UWs are used in at least two ways in a DC: (1) as areas for order picking, where products are often received and shipped in pallet quantities (e.g., distributors of groceries or appliances), and (2) as areas reserved to replenish fast-pick areas. UW designs take account of the general type of warehouse operations (e.g., single-command, dual-command), the number and location of the P&D points, and several aisle characteristics (Masae et al., 2020a).

The current literature discusses three primary UW design variants: conventional, non-conventional, and general warehouses. Among the three variants, the conventional and non-conventional designs were commonly employed in UWs (e.g., Gue & Meller, 2009; Meller & Gue, 2009; Feng et al., 2018), which is central to this study. As expounded by Masae et al. (2020a), conventional warehouses have "rectangular shape with parallel picking aisles that are perpendicular to a certain number of straight cross-aisles" (Fig. 1, left). Subsequently, warehouses with more than two cross-aisles are often referred to as multi-block warehouses, where each block in the warehouse consists of several sub-aisles (Fig. 1, right) (Masae et al., 2020a).

In a conventional warehouse, storage racks are arranged to create parallel picking aisles, perhaps with one or more cross-aisles, to allow workers to move quickly between picking aisles. This structure forces workers to travel rectilinear distances (i.e., north-south and east-west) to picking locations. On the other hand, non-conventional warehouses do not arrange all picking aisles or cross-aisles parallel to each other but "select a different layout to facilitate reaching certain regions of the warehouse or to improve space utilization" (Masae et al., 2020a).

While the conventional design is popular in the industry, several inadequacies were highlighted. For instance, in a conventional warehouse, it is always necessary to traverse the full rectilinear distance in a picking command (Cardona et al., 2012). Generally, it tends to limit productivity in a single-command UW (Gue & Meller, 2009; Meller & Gue, 2009; Cardona et al., 2012; Clark & Meller, 2013; Feng et al., 2018). This contention leads to the question of how to arrange cross-aisles and picking aisles to minimise the expected distance to pick in a single-command unit-load warehouse (Gue & Meller, 2009). To answer this question, non-conventional designs were developed. The literature presents six non-conventional UW designs, namely the U-shaped, Chevron, Leaf, Butterfly, Fishbone, and Flying-V designs (e.g., Glock & Grosse, 2012; Venkitasubramony & Adil, 2016; Feng et al., 2018; Masae et al., 2019; Masae et al., 2020a; Masae et al., 2020b). These designs present a noticeable reduction in expected single-command distance (Öztürkoğlu et al., 2012; Öztürkoğlu, 2016).

The U-shaped layout consists of a central aisle arranged in the form of a "U". It is also composed of various picking aisles extending from the central aisle. The problem of this design lies primarily in its narrow aisles, which restrict the mobility of picking devices aside from restricting traffic in its central aisle (Masae et al., 2020a), which may not be suitable in some UWs. On the other hand, the Chevron, Leaf, and Butterfly designs are similar to the Fishbone design (Öztürkoğlu et al., 2012). As a consequence of their insignificant difference, Öztürkoğlu et al. (2012) claimed that similar benefits to the Fishbone design could be expected under turnover-based storage.

The Flying-V design challenges the first design assumption of the conventional design, which presumes that cross-aisles are straight and meet picking aisles only at right angles. In this design, a cross-aisle is inserted into the storage space and does not constrain it to meet the picking aisles only at right angles (Fig. 2). On the other hand, the Fishbone design challenges the second design assumption of conventional warehouses, which presumes that picking aisles must be parallel to one another (Fig. 3). These two UW designs — the Flying-V and Fishbone designs — are the most widely studied UW designs in the literature (Masae et al., 2020a). Based on the previous discussions, this study focuses on the Flying-V and Fishbone designs.

Although the Flying-V and the Fishbone design both utilise a V-shaped cross-aisle, they are relatively different in other aspects. For instance, the proponents of the two designs (Gue & Meller, 2009) recognised that "travel in a Fishbone warehouse is much simpler than travel in a Flying-V warehouse". For this reason, comparative assessments were commonly employed in previous literature to identify which

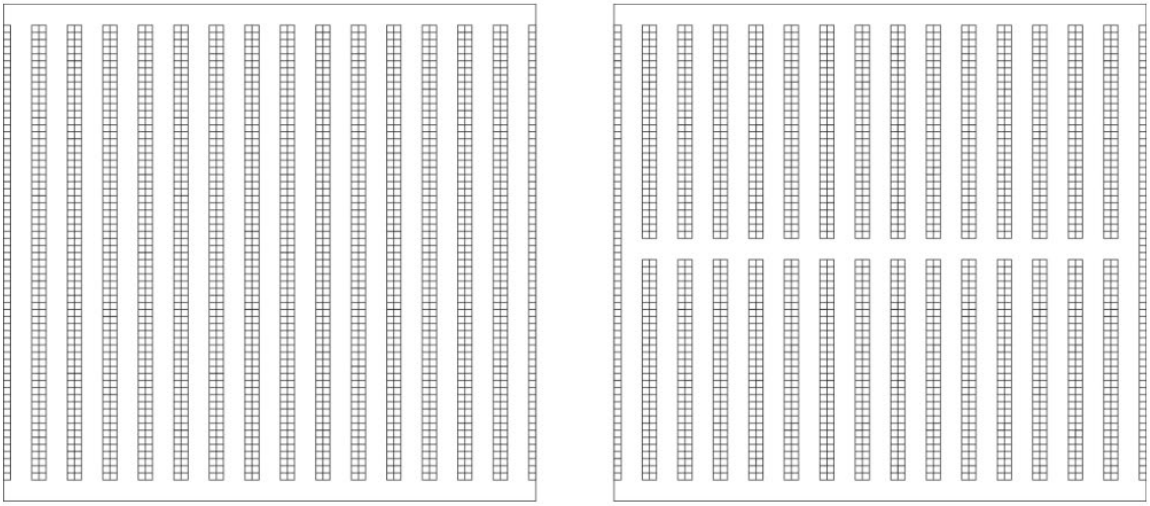

Fig. 1. Conventional design

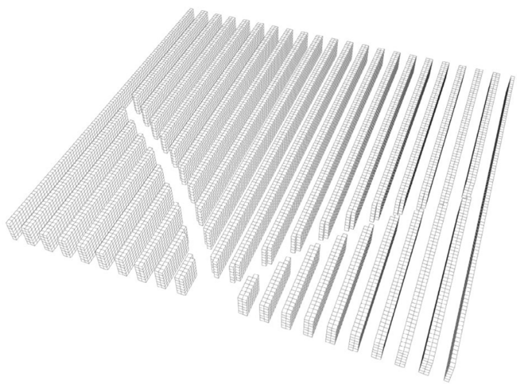

Fig. 2. 3D Flying-V design

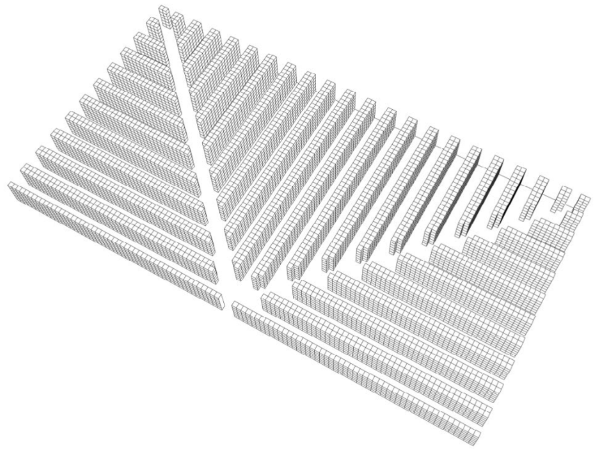

Fig. 3. 3D Fishbone design

among the two prominent UW designs possess more utility (Pohl et al., 2011; Gue et al., 2012; Clark & Meller, 2013; Masae et al., 2020a). Based on analytical approaches employed in the literature, the Fishbone design is collectively considered more superior than the Flying-V design.

While the literature offers several analytical studies on Flying-V and Fishbone designs, their comparative assessment in a real case environment is relatively unexplored. Furthermore, UW design primarily aims to maximise picking efficiency, one of the key performance indicators for measuring the flow of goods in warehouses is the picking run-time, which is highlighted as among most critical metrics for warehouse managers in the WERC (Warehousing Education and Research Council) survey (Öztürkoğlu & Hoser, 2019). Counterintuitively, the current literature contains no attempts to consider picking run-time in evaluating UW designs. This gap may be consequent to the limitations of analytical approaches.

Usually, to treat a problem analytically (i.e., considering an analytical approach is possible), one needs to resort to some assumption or approximation, e.g., an assumption that pickers are equally efficient in traversing through different UW designs with equal travel distances; hence, equal picking run-time. However, real-life situations are more complicated. For instance, an increase in the number of turns required to traverse through aisles in a UW design would increase travel time due to slowing down due to turns. However, this factor is avoided by analytical approaches through assumptions or approximations together with several other factors (e.g., randomness, asymmetry). Thus, employing other methods that allow studying factors not yet tractable with analytical methods is warranted for evaluating UW designs.

To bridge the gaps, this research employs a heuristic approach aided by the FlexSim software package in the comparative assessment of the conventional, Flying-V, and Fishbone design. The assessment is made in a real-case environment in a Philippine manufacturing company as part of a UW design improvement project. This study aims to provide a mix of theoretical and pragmatic perspectives in UW design. The novelty of this paper is three-fold. First, it pioneers the proposal of an easy-to-adopt approach to UW design for industry practitioners. Second, it is the first to employ the integration of picking run-time, travel distance, and capacity as performance assessment metrics for UW design. Lastly, it is among the first to illustrate an assessment of conventional and non-conventional (e.g., Flying-V and Fishbone) UW designs in a real case scenario, verifying the findings of previous studies employing analytical methods.

1. Literature review

1.1. Warehouse aisle design problem

Warehouse design is complicated because many interrelated design problems lead to many potential designs (Pohl et al., 2009a). There are three main problems in warehouse design. The first is the aisle design problem, which deals with the layout of storage space. The second is product allocation, which tries to find the right positioning of products in the storage space. The third is the order picker routing problem, which determines the best sequence of locations for a worker to visit when building orders. The first problem — the aisle design problem — is the primary concern of this paper. The following discussions elucidate the evolution of studies dealing with the aisle design problem.

Space is the primary concern in warehouse aisle design because its main objective is to store stocks. Moder and Thornton (1965) explored how floor space utilisation is affected by some dependent and independent variables. Among the independent variables affecting floor space is the "slant angle of the pallets". Their study proposed a mathematical model for assessing the extent that floor space change concerning the angle of placement of the pallets and aisle width. More recent studies on modelling warehouse aisle designs have been grounded on the idea proposed by Moder and Thornton (1965) (Öztürkoğlu, 2016; Kocaman et al., 2021; Öztürkoğlu & Hoser, 2019).

Following the work by Moder and Thornton (1965), Francis (1967a, 1967b) investigated the shape of optimal warehouse designs considering a single dock with rectilinear travel between the storage space and the dock. Elements of warehouse layout, such as space utilisation and travelling cost of a handling unit, were investigated by Berry (1968), who proposed two types of UW design from his findings. As pointed out by Öztürkoğlu et al. (2012), the first design assumed "rectangular pallet blocks with the same depth arranged around a main orthogonal gangway". On the other hand, the second layout assumed that "floor stored pallets were arranged in different depths around a single diagonal gangway providing access to all stacks" (Öztürkoğlu et al., 2012).

Building on the ideas previously discussed, Pohl et al. (2009b) showed that the optimal placement of a "middle" cross-aisle in conventional rectilinear designs should be slightly behind the middle. Cross-aisles are appropriate for order picking operations, in which more than one location is visited per trip but may not be applicable in single-command operations (Öztürkoğlu et al., 2012), which is an idea considered in this study. In conventional designs, workers travel rectilinear paths to store and receive pallets. However, this design generally limits the productivity of operations. For instance, the conventional design is based on several undocumented and unnecessary assumptions. Why, for instance, must cross-aisles meet picking aisles at right angles? Or why do picking aisles have to be parallel? The answer, of course, is that they do not, and various works have shown that adhering to these haphazard assumptions, which, by the way, is the most commonly adopted practice in the industry, could result in a significant penalty in labour costs (Gue & Meller, 2009; Pohl et al., 2011; Gue et al., 2012; Clark & Meller, 2013; Masae et al., 2020a).

To address this problem with the conventional design, "radial aisles" were proposed in previous studies. White (1972) showed that "radial aisles" reduced travel distance in a non-rectangular UW design. With the assumption of continuous warehouse space, he proved that travel distance from the P&D point to any point in the storage area was close to the Euclidean distance when the number of radial aisles increased. Gue and Meller (2009) extended this idea to propose two non-conditional designs to reduce single-command travel under a random storage policy, namely the Flying-V and Fishbone designs. The following discussions present the related literature that expounds on the Flying-V and Fishbone designs.

1.2. Flying-V design

In the Flying-V, picking aisles are parallel with orthogonal cross-aisles at the warehouse's top and bottom (Pohl et al., 2011). According to Gue and Meller (2009), for reasonable values of cross-aisle width, the optimal shape of the cross-aisle is V-shaped, with the vertex at the P&D point. The Flying-V aisle appears to be curved, but the cross-aisle segments between picking aisles are piecewise linear (Pohl et al., 2011).

The assessment of Gue and Meller (2009) on the Flying-V design yielded a 10% improvement in single-command travel under a random storage policy when compared to an equivalently sized conventional design with no middle cross-aisle. Under the same conditions, Feng et al. (2018) made a comparison of the Flying-V to the conventional design using optimal locations for P&D points determined by an optimal integer programming model. The results of their analytical evaluations show that the Flying-V design can obtain 8–18% distance savings compared to the conventional design (Feng et al., 2018).

Öztürkoğlu (2016) investigated the effects of various P&D points on both the capacity and the travel distance of non-conventional warehouses, including the Flying-V design. Their results revealed that the Flying-V design, in general, requires 61.17% less space than the improved designs in the study. They also found out that as the number of P&D points increases (greater than 11), the Flying-V design "overwhelms the improved designs because it requires less additional space" (Öztürkoğlu, 2016). Clark and Meller (2013) developed a three-dimensional model, which confirmed that "the Flying-V design is advantageous to implement over the standard (conventional) warehouse configuration".

1.3. Fishbone design

The Fishbone design has orthogonal cross-aisles at the top, left, and right edges of the warehouse (Pohl et al., 2011). The middle cross-aisle is diagonal and straight, with vertical picking aisles above and horizontal picking aisles below. The middle cross-aisle slope is calculated by minimising the P&D distance to a single random location in the warehouse. The assessment of Pohl et al. (2009a) revealed that, under a random storage policy, the Fishbone design reduces single-command travel by up to 20% and dual-command travel by 10–15% when compared to the conventional design.

Pohl et al. (2009b) explored the Fishbone design for task interleaving operations. Their analytical evaluations showed that the Fishbone designs offer a decrease in expected travel distance over several conventional conditional designs. The underlying notion is that a cross-aisle that cuts diagonally across the picking aisles affords "Euclidean efficiencies" (Gue & Meller, 2009; Cardona et al., 2012), which allows workers to get to most picking locations. In an analytical assessment performed by Clark and Meller (2013) on the robustness of non-conventional designs in terms of vertical travel, it was shown that, while their per cent improvement generally diminishes as the height of the rack increases, the Fishbone design maintains a greater per cent improvement over the Flying-V design. Its design, considering vertical travel, was then later formalised by Cardona et al. (2015).

Dukic and Opetuk (2012) and Çelik and Süral (2014) performed an evaluation of the Fishbone design for order-picking systems while considering different routing policies. Their analytic approaches discovered that the Fishbone design could perform as much as around 30% worse than an equivalent conventional design under a random storage policy and steady demand. They also found that depending on how skewed the demand is, the Fishbone design can outperform the conventional design for dedicated storage with non-uniform demand.

1.4. Synthesis of the review and research gaps

While the Flying-V design shows an advantage over the conventional design, that advantage diminishes as the number of levels in a warehouse increases (Clark & Meller, 2013). Thus, if the warehouse is large enough, then the Flying-V design is a better choice. However, if the warehouse is small, the conventional design is more suitable. Also, provided that the number of P&D points is fixed, and their positions are optimal, the Flying-V design seems to sacrifice some space to achieve the distance saving goal (Feng et al., 2018). Much like the Flying-V design, in gaining an advantage in terms of travel distance, the Fishbone design requires approx. 5% more space (Pohl et al., 2009b).

While these inadequacies may draw interest from an academic perspective, in most industries, the luxury of space may not be as abundant as analytical approaches, implicitly suggested via assumptions. In a fixed-space layout, the contention now turns to whether the Flying-V and Fishbone designs are still capable of outperforming the conventional design in terms of crucial indicators, such as picking run-time, travel distance, and capacity. Note that while picking run-time has been recognised as a vital performance indicator of UW design (Öztürkoğlu, 2016), it is not yet used in the assessment.

These contentions on the Flying-V and Fishbone designs warrant further investigation, especially in areas unexplored in the current literature. For instance, in assessing both the Flying-V and Fishbone designs, analytical approaches are commonly utilised (e.g., analytical experiments). For a study aimed at warehouse designers in practice, this approach might be insufficient. Real case applications are seldom employed in recent literature. Furthermore, the trend of employing analytical approaches for assessing UW designs has somehow led the current literature to disregard the provision of friendly approaches for warehousing practitioners in the industry to replicate assessment procedures. Analytical approaches also tend to oversimplify the complex nature of UW designs, often avoiding several design complexity factors, e.g., slow-down at turning points, which has dire effects on picking run-time — the completion time of a picking routine. These factors indicate that travel speed is not constant at all points of the layout. It varies especially at the turning points because the picker's rotational motion reduces vehicle speed (e.g., forklift speed). This explanation indicates that UW designs may have the same total travel distance yet different picking run-time. Several other factors may affect picking run-time, e.g., randomness, aisle width, and layout asymmetry. These factors are challenging to integrate into an analytic model, which explains why most models impose assumptions to avoid them.

1.5. FlexSim simulation software

Computer-simulation methods are by now an established tool in many branches of science. The motivations for computer simulations of physical systems are manifold. One of the main motivations is the elimination of assumptions and approximations. With a computer simulation, analysts can study systems not yet tractable with analytical methods. The computer simulation approach allows studying complex systems and gaining insights into their behaviour. Complexity, which is persistent in real-world applications, can go far beyond the present analytic methods. Since they can be used to study complex systems, computer-simulation methods provide standards against which approximate theories, e.g., analytical evaluations, may be compared.

FlexSim software integrates virtual reality technology and discrete object-oriented simulation. At present, the FlexSim simulation is primarily used in logistics, warehouse optimisation and design, and the optimisation of production lines (Tang et al., 2013; Liu et al., 2016; Kęsek et al., 2018). The applications of virtual reality technology and object-oriented simulation technology in assessing UW designs are unexplored. Thus, there is a need to explore the use of computer simulation to study UW designs' efficiency and compare results with analytic approaches employed in the literature. To address the gaps mentioned in this section, this study developed an assessment framework that utilises the FlexSim software for simulating the conventional, Flying-V, and Fishbone designs based on a real case from a Philippine manufacturing company. The performance indicators used for the comparative assessment are "picking run-time", "travel distance", and "capacity." The methodology used in this study is illustrated in the following section.

2. Methodology

This study employs a quantitative approach in assessing the performance of conventional, Flying-V, and Fishbone designs. Since the available analytical approaches in the literature seem incapable of assessing the indicator 'picking run-time' to evaluate this performance indicator, a simulation-based approach is adopted in this study, using the FlexSim software package as the main instrument. FlexSim is a widely adopted warehouse layout model simulation software in practice and is broadly discussed in the current literature (Huihui et al., 2016; Yafei et al., 2018), which allows designing, testing, and redesigning the layout of the warehouse ahead of commissioning projects and without risk to on-going operations. In this simulation, single-command operation and random picking are assumed. The detailed procedure adopted in this work is as follows:

Step 1. (Develop the warehouse blueprint) Measure the dimensions of the warehouse and develop a blueprint.

Step 2. (Estimate relevant parameters) Based on the developed warehouse blueprint, determine the relevant parameters for the simulation. This study adopted the standard geometry of the V-shaped non-conventional UW design introduced by Öztürkoğlu (2016), as illustrated in Fig. 4. The description of the parameters and features is presented in Table 1.

The required computations for each feature are distinct for the Flying-V and Fishbone designs. The

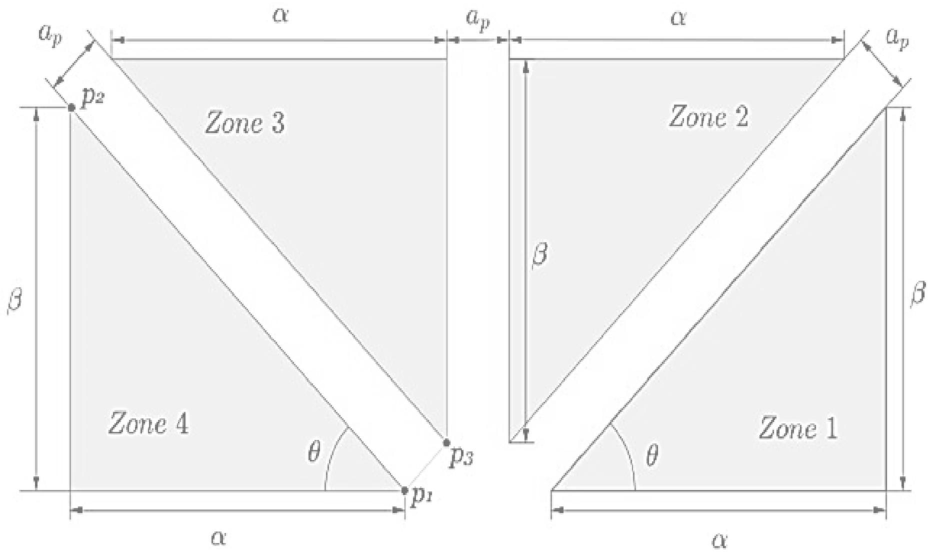

Fig. 4. Standard geometry of V-shaped non-conventional UW designs
Source: (Öztürkoğlu, 2016)

diagonal aisle slope for the Flying-V and the Fishbone designs is illustrated in Equation (1) and Equation (2), respectively. The diagonal aisle angle is obtained using Equation (3) for both Flying-V and Fishbone designs. The length of the triangle's height is obtained for the Flying-V and Fishbone designs using Equation (4) and Equation (5), respectively. The length of the triangle base is calculated using Equation (6) and Equation (7) for the Flying-V and Fishbone designs, respectively. Lastly, the warehouse area for both Flying-V and Fishbone designs is determined using Equation (8).

Tab. 1. Description of the variables

Parameters	**Description**
e_w, e_l, e_h	Dimensions of the openings
a_1	Horizontal stacking space
a_2	Vertical stacking space
a_3	GMP space requirement from the pallet to the wall
a_p	Aisle width
Features	**Description**
m	The slope of the diagonal aisle
θ	The angle of the diagonal aisle
β	The length of the height of the triangle
α	The length of the base of the triangle
A	The width of the warehouse
B	The length of the warehouse

$$m_{flying-V} = \frac{e_l + a_p + 2a_2}{7(e_w + a_1)} \tag{1}$$

$$m_{fishbone} = \frac{e_l + a_p}{4(e_w + a_1)} \tag{2}$$

$$\theta = tan^{-1}(m) \tag{3}$$

$$\beta_{flying-V} = u + 8e_w + 7a_1 + 2 \tag{4}$$

$$\beta_{fishbone} = u + 4e_l + a_1 + 2a_p + 1 \tag{5}$$

$$\alpha_{\ flyng-V} = 3a_p + 5a_2 + 2a_2 + a_c \tag{6}$$

$$\alpha_{\ fishbone} = a_3 + 10e_w + 9a_1 + 3.25 \tag{7}$$

$$Area = (AB|\ A = 2\alpha\ , B = \beta) \tag{8}$$

Step 3. (Set-up the simulation conditions) Using the FlexSim software, the simulation was executed using the following conditions: each palletised unit weighs 1000 kilograms, the average moving speed of the forklift is 5 metres per second, its average lifting speed is 0.45 metres per second, and the items in the warehouse are randomly picked. The blueprint, along with the computed variables, is recorded into the FlexSim with the pre-determined conditions.

Step 4. (Run the simulation) The simulation was run for a different number of random picks, $\delta = (30{,}80) \in \mathbb{Z}^{+}$, for the conventional, Flying-V, and Fishbone designs. The performance indicators measured in this simulation are 'picking run-time,' 'travel distance,' and 'capacity.' In visualising the flow of this heuristics approach, a Heuristic Comparative Assessment of the UW Designs (HCAUD) framework is presented in Fig. 5.

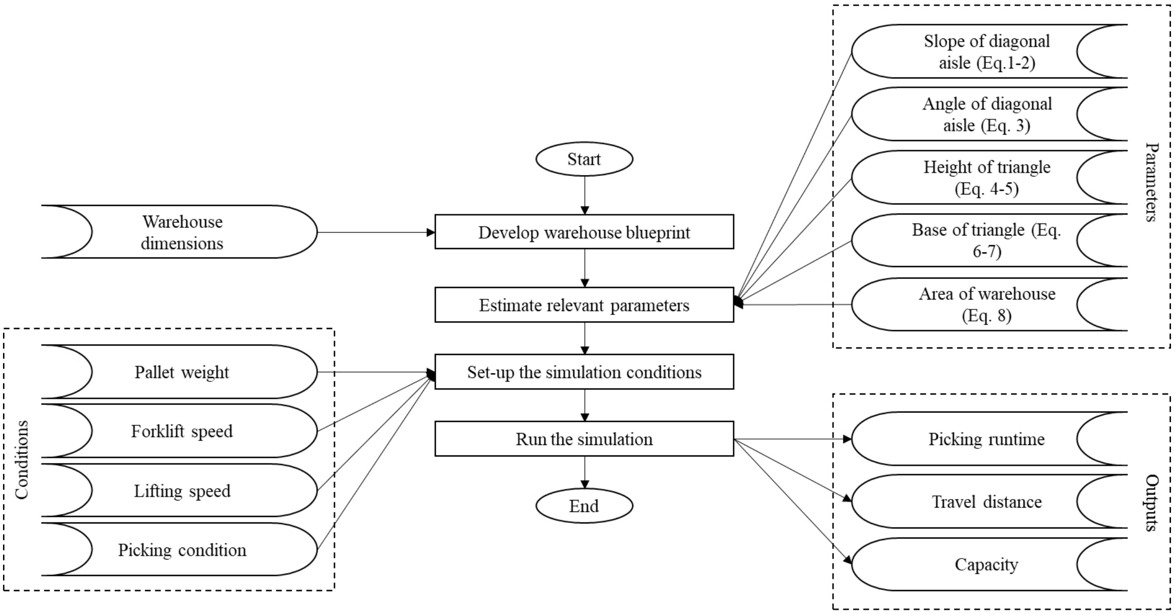

Fig. 5. Heuristic comparative assessment of UW designs (HCAUD) framework

3. Case study: Shemberg Marketing Corporation

3.1. Plant Linearisation Program (PLP)

A Philippine carrageenan manufacturing company, Shemberg Marketing Corporation, intends to implement a Plant Linearisation Program (PLP), wherein a re-layout of the entire plant would be conducted. The scope of the PLP involves the re-design of individual production, warehousing, and other facilities.

In line with this, the company's Blending Area, Magnetising Area, and Primary Blended Powder Warehouse (PBPW) are proposed to be situated in one building, as presented in Fig. 6. The Blending Area requires a space allocation for its accessories, mainly comprised of chemicals and powder ingredients.

The blenders would require a maximum of 20 tons or 20 pallets worth of accessories each. In the proposed linearisation layout, there is no space allocation for the accessories. The management intends to reduce the PBPW to utilise more space for the Blending Area.

Despite the possible reduction in space, the PBPW has to be re-designed so that travel distances from the P&D point and picking run-times are kept at a minimum while maximising warehouse capacity. In line with these objectives, this study incorporates the Flying-V and Fishbone design.

3.2. Design specifics

Zooming into the PBPW in the initial design of the PLP, the specific dimensions of the conventional design are presented in Fig. 7. For the capacity improvement, the initial design of the PBPW in the PLP is modified to propose an alternative layout. The said design is much like the conventional design, but with a_p=2.7 metres. Furthermore, the Flying-V and Fishbone design of the PBPW is presented in Figs. 8 and 9, respectively.

4. Simulation results

Based on the design specifics provided in Figs. 6 to 9, each UW design's parameter and design feature was computed using Equations (1) through (8). The results are presented in Table 2. The Flying-V and Fishbone designs occupy relatively less space than conventional designs (e.g., initial PLP design, alternative PLP design). With this, the Flying-V and Fishbone designs exhibit 7.5% and 5.0% more capacity than the conventional designs. The calculated parameters and features and the specific designs for the UW designs assessed in this study were entered into the FlexSim software for running the simulation. The results of the simulation are presented in the following discussion.

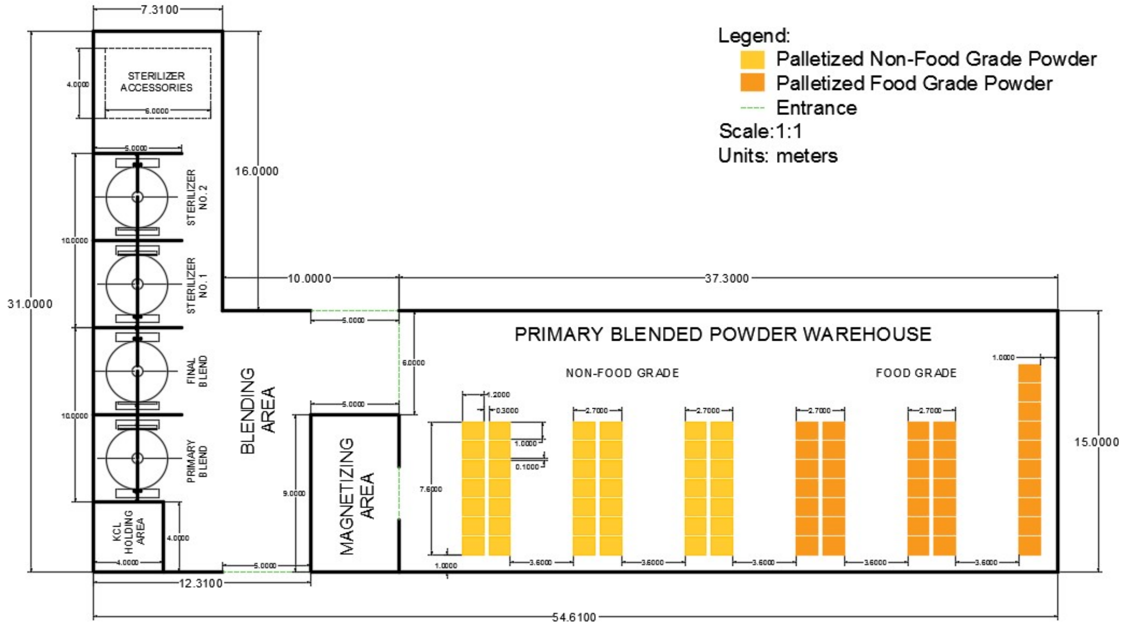

Fig. 6. Initial design based on the PLP

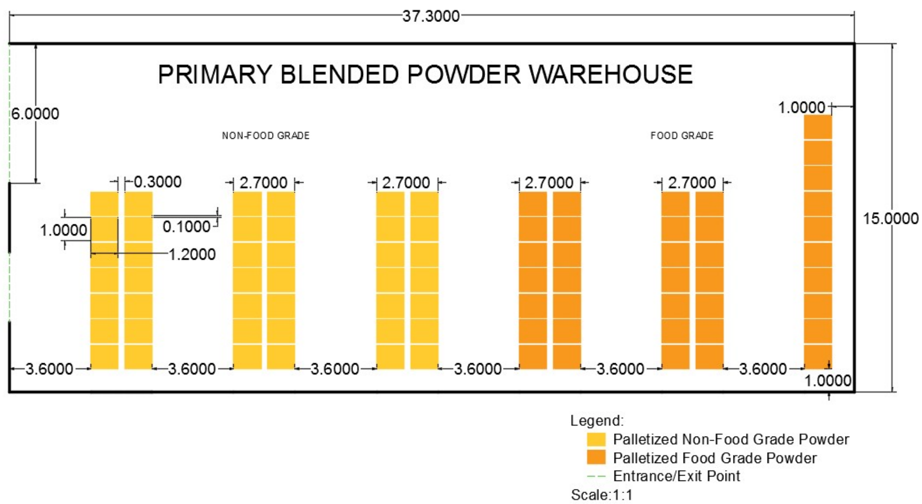

Fig. 7. Conventional design of the PBPW

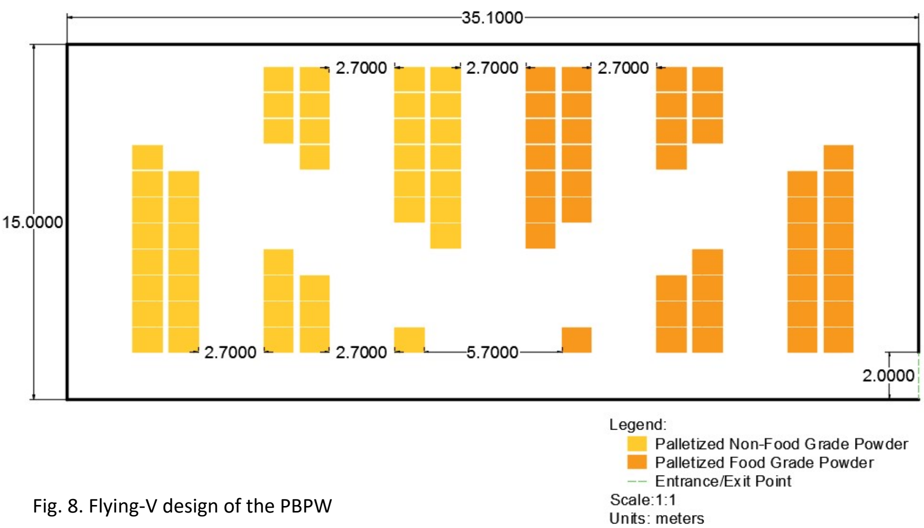

Fig. 8. Flying-V design of the PBPW

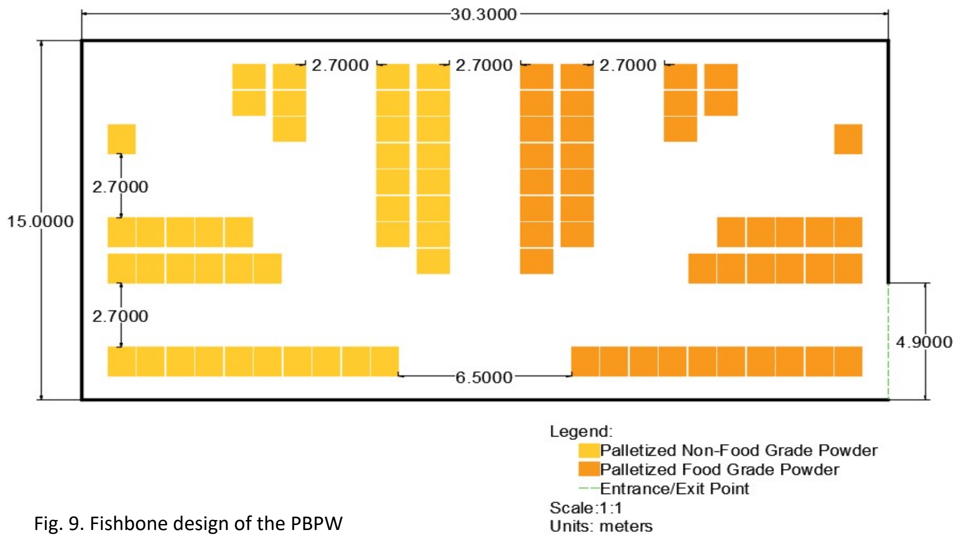

Fig. 9. Fishbone design of the PBPW

Tab. 2. Calculated parameters and features

Parameters	Unit	Initial PLP Design	Alternative PLP Design	Flying-V Design	Fishbone Design
e_w	metres	1.00	1.00	1.00	1.00
e_l	metres	1.20	1.20	1.20	1.20
e_h	metres	1.00	1.00	1.00	1.00
u	metres	-	-	4.30	2.00
a_1	metres	0.10	0.10	0.10	0.10
a_2	metres	0.30	0.30	0.30	0.30
a_3	metres	1.00	1.00	1.00	1.00
a_c	metres	-	-	2.85	3.50
a_p	metres	3.60	2.70	2.70	2.70
Features					
m	metres	-	-	0.94	89.00
θ	degrees	-	-	43.00	42.00
β	metres	-	-	15.00	15.00
$\propto$	metres	-	-	17.55	15.15
A	metres	37.30	37.30	35.10	30.30
B	metres	15.00	15.00	15.00	15.00
$Area$	square metres	559.50	559.50	526.50	454.50
$Capacity$	pallets	80.00	80.00	86.00	84.00

The simulation results revealed that the Fishbone design consistently outperformed the Flying-V, initial PLP, and alternative PLP designs in terms of picking run-time. Moreover, the disparity of the results also tended to diverge as the number of random picks increased, which made the advantage of the Fishbone design more elaborate. While less advantageous than the Fishbone design, the Flying-V design was relatively superior to the conventional designs in picking run-time. The comparison of picking run-time of the UW design assessed in this study is presented in Figure 10. The results reveal the following ranking in terms of picking run time: Fishbone design > Flying-V design > alternative PLP design > initial PLP design.

The simulation results also revealed that the Fishbone design consistently outperformed the other UW designs assessed in this study in terms of travel distance. Interestingly, the Flying-V design seemed to fail at this performance indicator by an overwhelming extent compared to other UW designs. The alternative PLP design, on the other hand, appeared to have relatively the same results as the initial PLP design. A comparison of the UW designs' travel distance over the different picks is presented in Fig. 11. In general, the results reveal the following ranking in

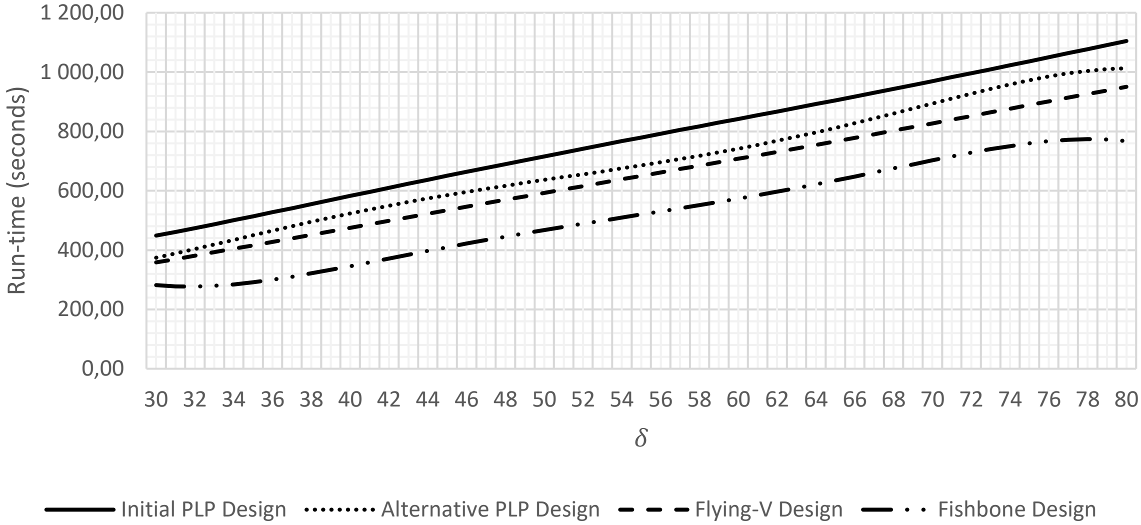

Fig. 10. Comparison of picking run-time

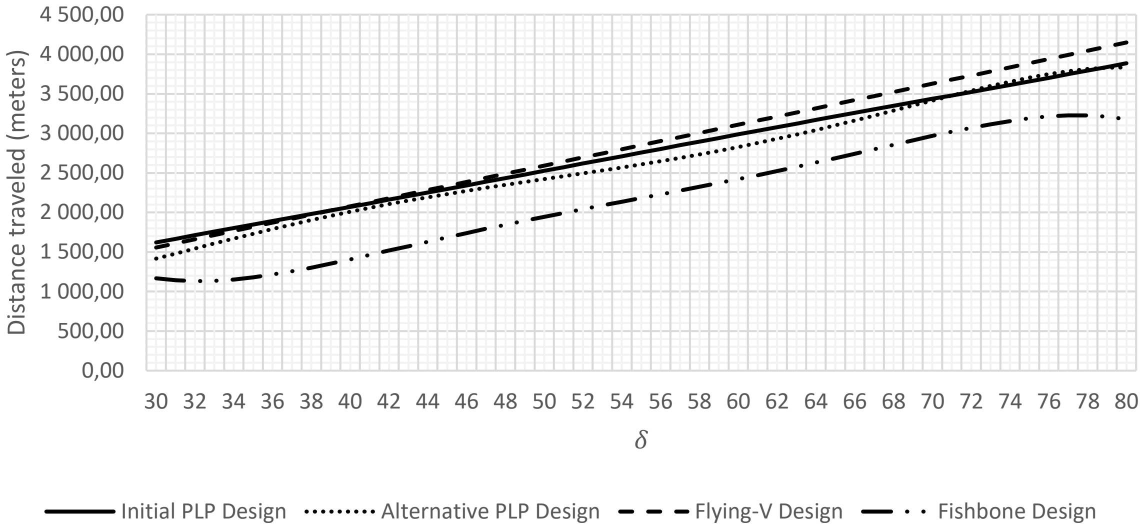

Fig. 11. Comparison of travel distance

terms of travel distance: Fishbone design > alternative PLP design > initial PLP design > Flying-V design.

5. Discussion

Considering the initial PLP design as a reference point, in terms of picking run-time, as illustrated in Fig. 12, the per cent improvement of the Fishbone design, when compared to the other UW designs, is overwhelmingly large. The literature has always emphasised significant improvements with the Fishbone design in terms of travel distance (Pohl et al., 2011; Cardona et al., 2012; Dukic & Opetuk, 2012; Clark & Meller, 2013; Çelik & Süral, 2014; Cardona et al., 2015). However, no research produced the same results in terms of picking run-time, which is an equally important performance indicator if not more critical. This study provides the first insights on the performance of both conventional and non-conventional UW designs in terms of this metric. It is also worth noting that, while the Flying-V design presents more improvement than the alternative PLP design, the advantage is relatively insignificant because their functions are relatively close to each other. Furthermore, for all UW design, per cent improvement in terms of picking run-time seems to decrease as the number of random picks increases. In the case of the Fishbone design, while per cent improvement generally projects a downtrend together with the number of random picks, its function seems to fluctuate. The main implication of this observed behaviour lies in optimal random picks to allow that the maximised per cent improvement for the Fishbone design. In this study, 34–36 random picks seem to produce maximum utility for the Fishbone design.

Similar findings for the Fishbone design can be inferred in terms of per cent improvement for the travel distance. However, interestingly, the Flying-V design seems to exhibit unproductive results in this performance indicator. As illustrated in Fig. 13, the Flying-V design consistently fails to improve the initial PLP design. According to Feng et al. (2018), for the Flying-V design to exhibit improvement to the conventional design, it usually "sacrifices some space". Based on their analytical evaluations, they suggested that "if the warehouse is large enough, then Flying-V is a better choice"; however, "if the warehouse is a small size, the conventional aisle configuration is more suitable". Thus, in this case, the Flying-V design may have been unsuitable because of the warehouse's limited space. In this case, the conventional UW designs are preferred to the Flying-V design.

Furthermore, this study confirms the findings of previous studies that attempted to compare the Flying-V and the Fishbone design. Gue et al. (2012) emphasised that "the Fishbone design is generally preferred to the Flying-V", which can also be suggested based on this study's findings. In general, in terms of capacity, picking run-time, and travel distance, the Fishbone design is deemed the most advantageous design compared to the Flying-V, alternative PLP, and initial PLP designs.

The findings of this study suggest that among the UW designs considered for improving the PBPW as part of the PLP in the case firm, the proposed Fishbone design is most suitable. The final proposed

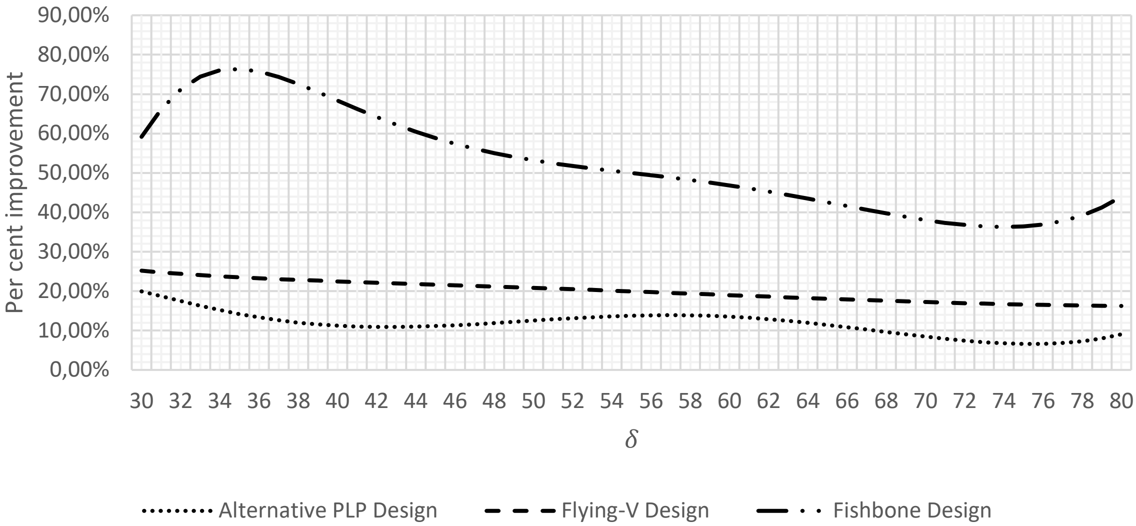

Fig. 12. Improvement in picking run-time

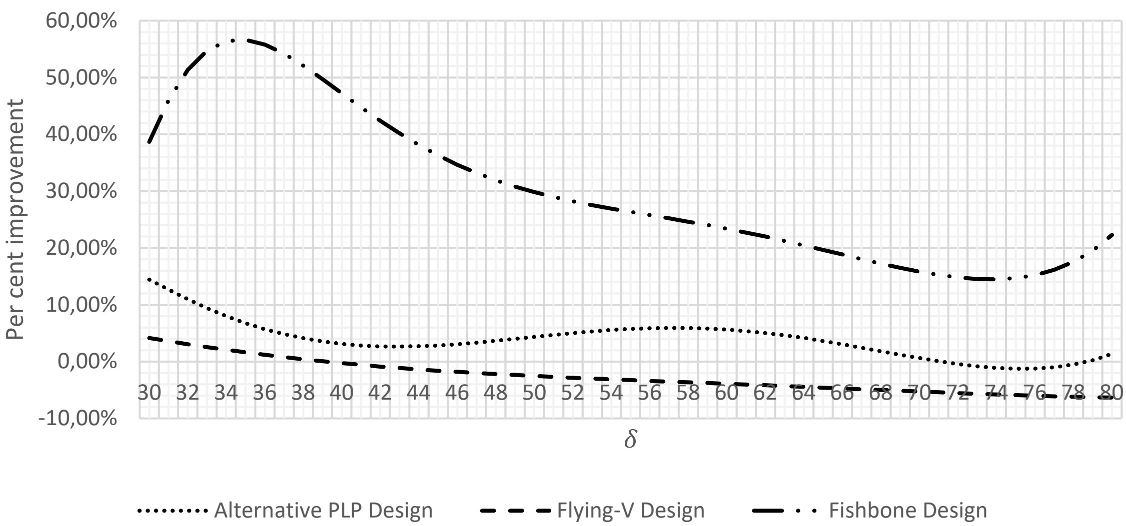

Fig. 13. Improvement in the travel distance

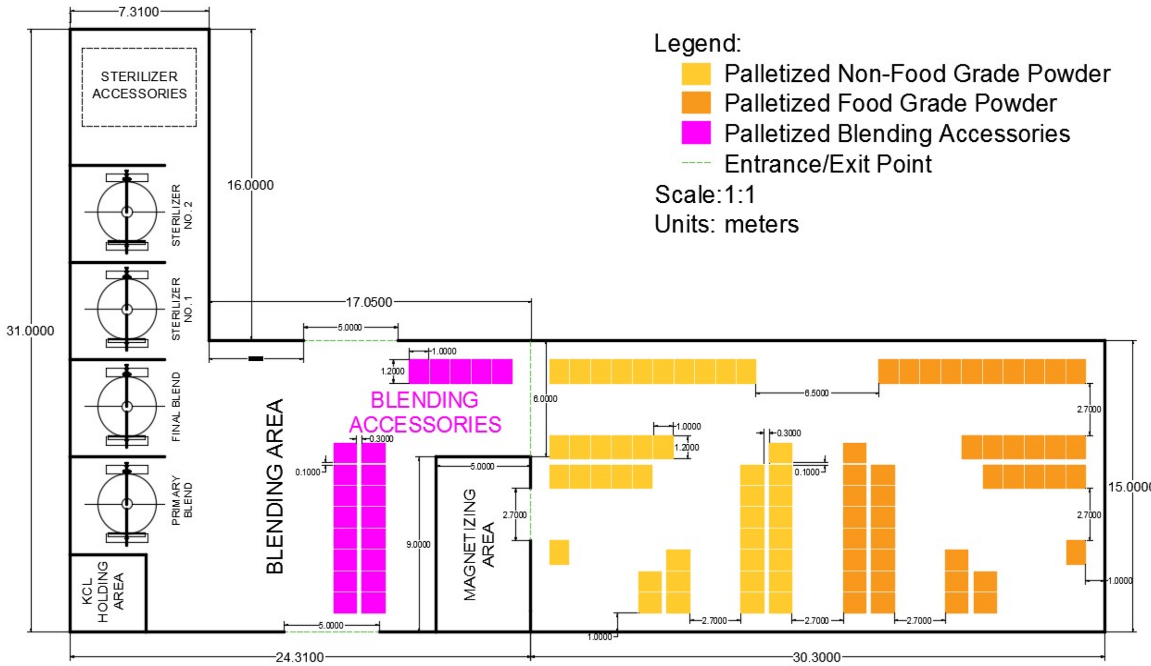

Fig. 14. Final proposed design integrating the Fishbone design in the PLP

design associated with the findings is presented in Fig. 14. With the proposed design, the company is expected to save, on average, 52.39% of picking run-time, 32.25% travel distance, and increase storage capacity by 7.5%. For future warehouse improvement projects, the framework developed in this study (HCAUD framework) can also be adopted. Compared to other approaches the developed framework, is more convenient and less complicated by a significant degree but produces relatively the same results. Thus, it can be easily replicated by industry practitioners for in-house warehouse assessments. The attempt to measuring picking run-time, which was successfully demonstrated in this study, expands the dimensions for evaluating warehouse designs. Thus, in selecting future UW design options, picking run-time may now be considered, which offers a more systematic approach for UW design selection. The study findings also demonstrate that while the Flying-V design was developed as an improvement of the conventional designs (Gue & Meller, 2009a), its application is limited by various factors such as warehouse space availability. In relatively small warehouses, similar to the warehouse under investigation of this work, a transition from conventional design to the Flying-V design may not be adequate.

Conclusions

The UW design approaches are continuously expanding with the improvements in systems analysis and decision-aiding tools. These potentially enhance the capacity of managers to develop, assess, and select UW designs, especially in the manufacturing sector. Among the first attempts in the literature explored in this article were (1) the development of a novel approach to a heuristic comparative assessment of non-conventional UW designs, (2) assessment of UW design in the context of a real-case scenario, and (3) the measurement of picking run-time as a performance indicator for assessing UW designs. The Flying-V and Fishbone designs were among the UW designs explored in this article. This work developed a framework based on the FlexSim software package for the convenient analysis of UW designs. The results suggest that the Fishbone design provides the most advantage compared to the Flying-V and the other conventional designs. The findings also supported previous literature that suggested limitations on the Flying-V design, implying that the Flying-V design may have been an unsuitable option due to the limited space of the warehouse. Based on the findings, a proposed UW design for the PLP was developed, integrating the Fishbone design. The company is expected to save, on average, 52.39% of picking run-time, 32.25% travel distance, and increase storage capacity by 7.5% with the proposed design. Furthermore, industry practitioners can quickly adopt the developed HCAUD framework for their in-house UW design assessments.

While this work considers multiple performance indicators for the UW design assessment, their integration in outranking the UW designs was not explicitly applied, which would have been a more systematic approach to outranking the alternatives. In this regard, for future research, a multi-attribute decision-making approach may be employed to address this gap. Furthermore, since this research case environment limits the Flying-V design's applicability, its comparison with the Fishbone design may be biased. Thus, future studies could replicate the procedures through the proposed framework in a more suitable setting, i.e., a relatively larger warehouse. Lastly, while several performance indicators have been identified in previous research, only several (three) performance indicators were measured in this study. Thus, it may be relevant to consider multiple performance indicators in the assessment of UW design while employing the framework proposed in this work.

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