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TRIZ trend of engineering system evolution: A review on applications, benefits, challenges and enhancement with computer-aided aspects

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ABSTRACT

Trend of Engineering system evolution (TESE) is a popular tool in the theory of inventive problem-solving (TRIZ). Because it is applicable in various domains, it has been extensively used in practical projects to develop engineering products and forecast new technologies. However, although its generic pattern makes it a versatile tool for inventing and discovering the next generation of engineering systems, the scope of its practical use in product innovation has yet to be critically explored. This includes the applicability of its trends and sub-trends, efficacy and benefits in product development, and challenges and limitations. Therefore, this review uses reliable and noteworthy studies to overview the use of TESE in science and explore the benefits and challenges associated with its practical use. TESE-based studies have been conducted to prove its usability in technological development and innovation. We recommend that TESE should be integrated with various computer-aided aspects, such as scientific information, patents, social networking, disruptive technologies, manufacturing, and robotics, to address existing limitations. In addition, this review validates that these five aspects have yet to be demonstrated cohesively. This review provides TESE practitioners with insights into the application of the trends and sub-trends of the TESE toolkit.

1. Introduction

Scholars and industrialists agree that a significant logical correlation exists between open markets and innovation. Under the concepts of “market pull” and “technology push”, this correlation is defined as a provision of market requirements via innovative production (Alex Lyubomirskiy, Litvin, Ikoenko, Thurnes, & Adunka, 2018). The trend of engineering system evolution (TESE) is a heuristic and predictive toolkit that can deliver either market pull, with the trend of S-curve analysis, or technology push, with its sub-trends (Ding, Yang, & Bao, 2012; Alex Lyubomirskiy et al., 2018; Mansoor, Mariun, & Ismail, 2013). The scientific legacy of Genrich Altshuller, the TESE toolkit, is the product of years of developing the vintage theory of inventive problem solving (TRIZ) (Altshuller, 1984; Ikoenko, 2003; Alex Lyubomirskiy et al., 2018; Souchkov & Mars, 1998). As the next step in the superior evolution of a system, the trends of evolution provide strategic roles to solve

problems encountered by technical systems, as well as corresponding solutions (Mann, 2007; Nähler & Gronauer, 2016).

This study examines the main concepts, particularly, the usability, benefits, and challenges of TESE. This includes an illustration of the expansion of TESE from its proposal until the present in Section 2. Thereafter, in Section 3, this review demonstrates how practitioners and researchers have innovated systems using TESE. The details of the systematic literature review adapted from (Barbara Kitchenham et al., 2009; B. Kitchenham & Charters, 2007) are a validation of measures as a means to objectively diagnose and scrutinise the research issue, as discussed in Section 4. This section also illustrates the global distribution of TESE based on available publications. Section 5 presents a comprehensive discussion of the benefits and limitations of TESE. Subsequently, Section 6 discusses the latest studies that have attempted to improve TESE using computer-aided techniques. Finally, theoretical contributions are presented to address gaps in the integration of TESE with

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Table 1
Altshullerian Laws.

Law Category	Laws
Static	1- Wholeness (completeness) of parts 2- Conductible energy flow 3- Coordination (harmonisation) of the rhythm of the different parts
Cinematic (Kinematic)	4- Increase in ideality (degree of idealness) 5- The unequal (uneven) development of the parts 6- Transition towards a super-system
Dynamic	7- Transition from a macro-level to a microlevel 8- Increase in dynamicity and controllability (substance-field or electromagnetic involvement)

computer-aided techniques to effectively enhance the usage of TESE. This study provides beginners and newcomers with concrete insights into their innovations. However, unlike many extant reviews that focus only on the use of TRIZ, this study focuses on providing informative, extensive, and fruitful recommendations for the improvement, as well as future, of TESE development.

2. Overview of TESE

2.1. Advent of TESE

TESE was inspired by Altshuller’s systematic and logical development trends, which were designed over 50 years ago (in 1970s), and is categorized into three types of roles: (1) three statistical roles related to sustaining system functions, (2) three cinematic roles in terms of evolving from the perspective of time or space, and (3) two dynamic roles bolstering the projection of an optimal and well-crafted system (Table 1) (Cavallucci, 2001; Jing, Xiangmin, & Kai, 2019; Alex Lyubomirskiy et al., 2018; Petrov, 2019b; Verhaegen, D’hondt, Vertommen, Dewulf, & Duflou, 2009).

Altshuller proposed these laws, later referred to as trends, to highlight the challenges of sophisticated invention and engineering systems under the concept of the theory of inventive problem solving (TIPS), which is more commonly known by the Russian term “teoriya reshniya izobretatelskikh zadatch (TRIZ)” (Chulvi & Vidal, 2011; Alex Lyubomirskiy et al., 2018; Petrov, 2019b; Teplov, Chechurin, & Podmetina, 2017). Indeed, the laws of the abovementioned engineering systems are

prevalent and act as the basic trend in TRIZ (V. Souchkov & Mars, 1998).

For clarity, terms and words such as “laws, trends, patterns, and lines of the technical system, engineering system, S-curve, or directed evolution” are synonyms that refer to TESE (Valeri Souchkov, 2016).

2.2. Evolutionary trends

Introducing the laws of evolution in engineering systems has made the design and creation of products coherent and objective (V. Souchkov & Mars, 1998). In 2003, TRIZ researchers realised that the laws were general and that undiscovered trends existed that could outline the correlation between numerous parts of the system (Mann, 2003). This led Mann to introduce evolution trends into three different categories: (1) space, (2) time, and (3) interface (Fig. 1); each trend has 12, 6, and 17 sub-trends, respectively (Mann, 2003).

This led to the discovery of over 20 unique trends in business evolution, which describe how enterprises can increase both the quality and quantity of a project (Mann, 2003). However, this review does not discuss these.

The trends were designed to follow a logical sequence that represented progress and outlined both generic and specific trends in depth, in the hope of systematically solving a problem or strategising the technical “reason for the jump”, which is equivalent to predicting an evolution. Although Mann states that inventors are free to select any random method of system evolution, he recommends adopting these strategic categories to develop in a consistent manner and increase the probability of discovering possible technical trends (D. L. Mann, 2007).

Over the years, researchers and TRIZ practitioners have developed various approaches to this methodology. Therefore, a quantitative method that integrates the 52 above-mentioned trends was constructed to prioritise and rapidly distinguish the solution objective in TRIZ tools (Sheu & Chiu, 2017).

The application and optimisation of Industry 4.0 trends have been studied in the context of disruptive technologies, particularly, digitisation, Big Data, and the Internet of Things (IoT) (Nählera & Gronauerb, 2017). A novel approach that considers the correlation between machine and individual sensory organs, as well as compliments the trends shown in Fig. 1, was developed to evaluate and predict product development (Mayer, 2017). In addition, the advantages and efficacy of using the trends shown in Fig. 1 have been analysed to design eco-based

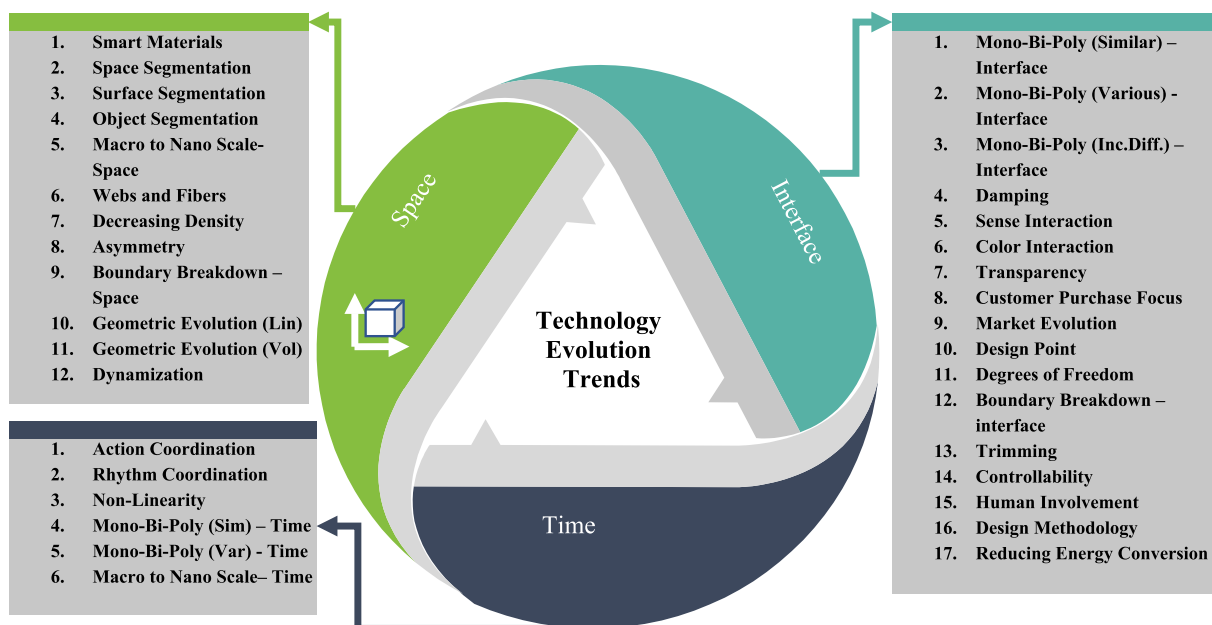


Fig. 1. Redrawn categorisation of technology trends (Mann, 2003).

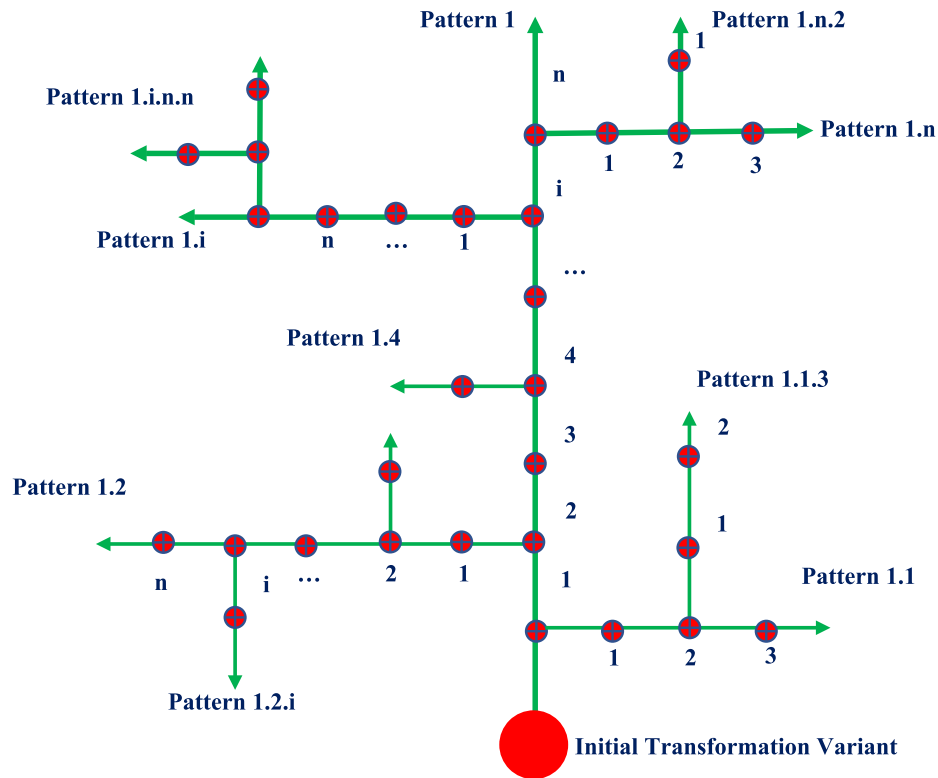


Fig. 2. Redrawn Evolution Tree (Shpakovsky, 2006).

products and their impact on environmental factors (Chulvi & Vidal, 2011). Other studies have examined the adoption of the trends listed in this section as a reference criterion for classifying and analysing patents utilising text mining techniques to attain advantages in the provision of research and development (R&D) (Wang, Chang, & Kao, 2010), property-function-based engineering design preparation (Yoon & Kim, 2012), and technology prediction (Yoon & Kim, 2011). For instance, Park, Ree, and Kim (2013) adapted evolutionary trends with a subject-action-object (SAO)-based text mining technique to evaluate the future promise of floating wind turbine patents, and Verhaegen et al. (2009) used a part-of-speech (POS) tagger to conduct patent analyses and measure evolutionary trends.

2.3. Evolutionary Tree

TRIZ masters have always sought to improve Altshuller's ideas in the hope of increasing the robustness of TRIZ and making its use in the evolution of systems more practical. Therefore, to overcome the vast amount of technical property data and dispersion of patent information, Shpakovsky (2006) proposed an "Evolution Tree" that initialises the problem, defines new ideas, and synthesises information.

Shpakovsky chose a tree metaphor to link the evolution of various elements of a system to a branch (Fig. 2). The evolution of a pattern along a branch denotes an improvement in a particular part of a technical system in the direction of the trends discussed in Sections 2.1 and 2.2. Typically, a fundamental pattern represents the main objective or action of a system, which is initiated in the early stages of the system design. Other patterns, principles, and branches evolve to demonstrate the different elements of a system, which have been amplified in both depth and breadth (Shpakovsky, 2006).

This structure is comparatively easier to implement and facilitates the prediction of future developments in a system based on the main function of evolution, thereby providing an overview of interrelated patterns by analysing existing patents (Lok, 2017). In addition, this approach enables educators to use creative, inventive, and

morphological technological developments to classify electric machines with a simpler and more effective analysis method (Bertoncelli, Mayer, & Papini, 2017). It also promotes creative thinking and design, which can be practiced globally (Berdonosov, 2015), and can also be used to predict the evolution of language programming in the context of solving object-oriented contradictions (Berdonosov, Zhivotova, & Sycheva, 2015). Moreover, inventors and engineers have numerous opportunities to create new products by identifying undiscovered developments of a system that align with missing trends in the branches (Mansoor, Mariun, & AbdulWahab, 2017; Rahim, Sheng, & Nooh, 2015).

Although Shpakovsky proved the strength of his proposed approach by bypassing the need for patents in his case study of washing machines, several researchers argued that further improvements were required, which led to the development of the patent circumvention framework (Li, Ming, Zheng, Xu, & He, 2013) and TRIZ-based trimming (Li, Ming, He, Zheng, & Xu, 2015). In addition, Smirnov (2020) criticised Shpakovsky's approach, as it had two considerable shortcomings. First, it lacked the criteria for selecting trends when developing functions, and second, it lacked mechanisms to apply the trends and enhance system functions.

2.4. Current state of TESE

The modern TESE architecture was schemed as a hierarchy (Ang, 2018) and encompasses a broad spectrum of theoretical research as well as goal-oriented innovations and developments in multiple engineering fields. The TRIZ team (GEN), formerly the TRIZ plus team and currently the TESE team, consists of world-class innovators among the most respected professionals in TRIZ studies (S. Ikonenko, 2004). Fig. 3 depicts TESE-related trends and sub-trends (Alex Lyubomirskiy et al., 2018).

The current TESE, known as the "network of evolutionary trends", supports the systematic functional analysis of real engineering devices and includes decomposition, information gathering, and modelling approaches (Chechurin, 2016). TESE is a method of trend-forecasting that

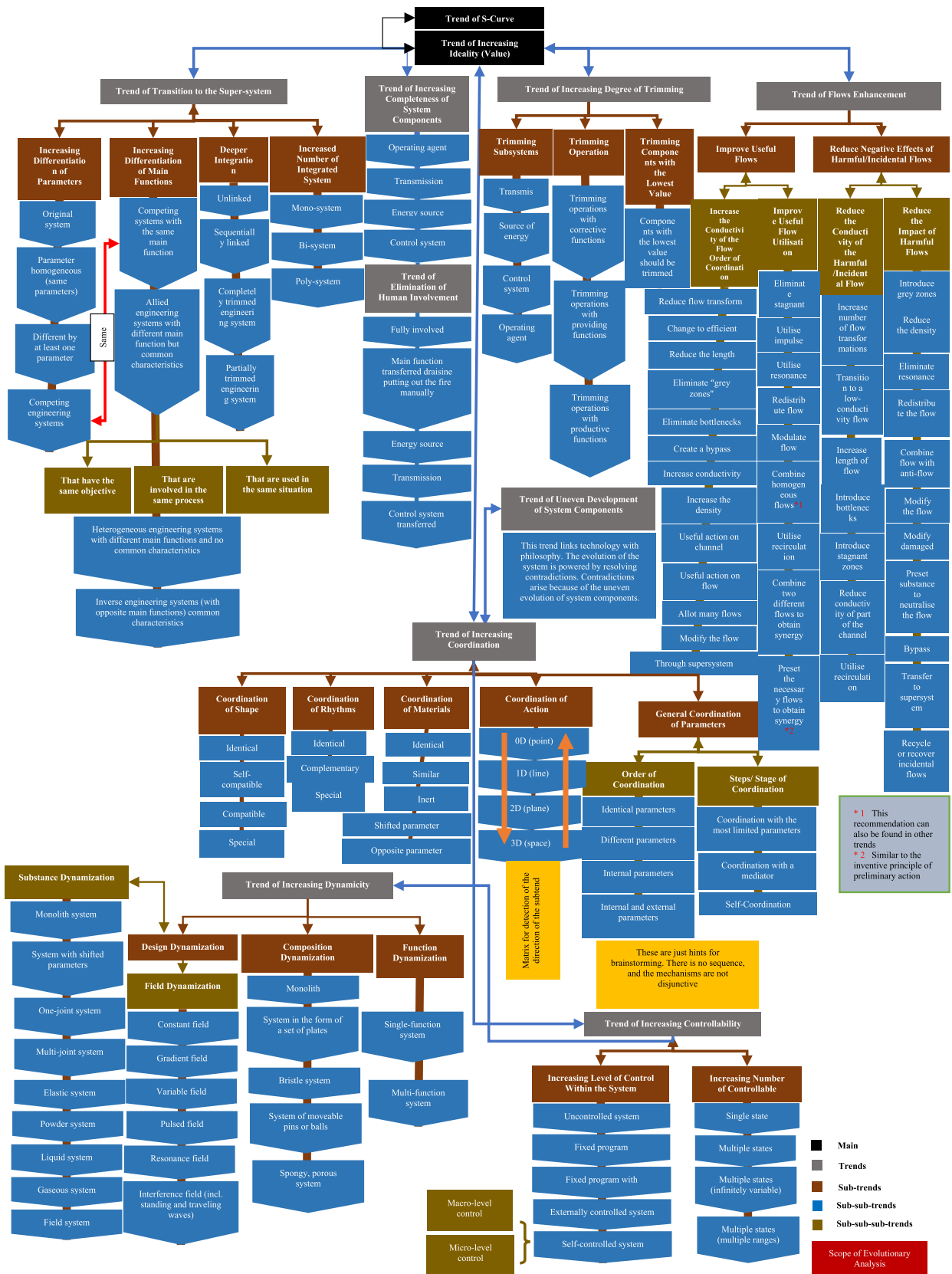


Fig. 3. Trends and sub-trends of TESE.

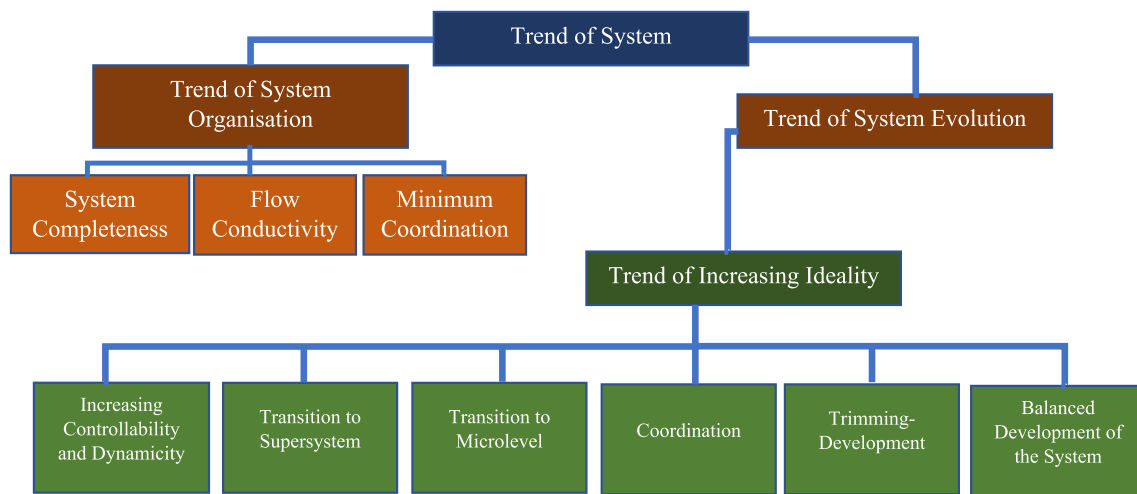


Fig. 4. Remapped structure of trends of system development.

is applicable for both designing new products as well as identifying and solving problems (Christoph, Christopher, & Udo, 2017). It consists of knowledge-based hierarchical objective patterns applicable to each level of the nested function model (NFM) of every engineering system (Horst Th. Nähler, 2016). In addition, it prevents waste and emissions during the production stage by providing function-based analyses, trimming, and ideality evaluations that align with cleaner production strategies (Leonid, Kalle, & Mika, 2015). Moreover, TESE helps reconstruct, adjust, compile, classify, and intensify traditional versions of TRIZ evolution trends (Lyubomirskiy, Litvin, Ikovento, & Thurnes, 2018). As the priority of a trend is examined based on its similarity, that is, “similar problems have similar solutions”, it determines the similarity of a problem model in the current stage of a trend and distinguishes improvements by jumping to another stage of the trend (Sheu & Chiu, 2017). TESE can also be combined with the multiscreen approach and NFM to create a comprehensive product map that serves as a basis to assess the ideality of a device and plan future strategies (Nahler & Gronauer, 2015). In a recent study, Mayer (2017) suggested adding human senses to TESE to address challenges that users encounter when interacting with a technical system.

TESE also universalises function-based analysis for all engineering and technical systems to identify problems, as well as theoretically and practically bolster corresponding solutions (S. Ikovento, 2004; Alex Lyubomirskiy et al., 2018). Therefore, it is commonly defined as a “statistically proven direction of engineering system development that describes the natural transitions of engineering systems from one state to another” (Sergei Ikovento, 2009). Multiple studies have quoted this definition (Chybowska & Chybowski, 2019; Jin, San, & Li, 2008; I. Mašin, 2020; Ivan Mašin & Petrů, 2018; Petrov, 2019b; Wismadi, 2020).

TESE is fundamentally based on Altshuller’s theory, in which the evolution of an engineering system is determined using a factual, reliable, and persistent measure that is not abstract but objective in nature. This is termed the “voice of the product” (Jantschgi, Scheffl, & Erkner-Sacherl, 2019) and provides a systematic and strategic platform consisting of trends and sub-trends that help forecast the next generation of products and technologies by evaluating the status and phase of technological trends. For instance, the correlation between the stages of the S-curve and TESE application roadmap has been studied to understand the maturity of Xiaomi smartphones for further development (Jing et al., 2019). In addition, core ejector system trimming has been investigated to generate new patents (Li et al., 2015). The level of inventiveness of silver sintering tools has been analysed using the trend of the increasing trimming degree such that useful functions are used to replace components with disadvantages (Shyong, Foo, & Xin, 2018). Additionally, the use of TESE in product innovation and development helps products

remain in tune with market competition (Ikovento, 2013). It also prevents the generation of unusable ideas and concepts that overlook objective trends in the evolution of an engineering system (Abramov, 2014b). TESE has been determined to systemise improvement routes and facilitate “winning” transitions, i.e., from one development stage to the next, while maintaining a consistent product-market fit (Mašin, 2020; Ivan Mašin & Petrů, 2018), particularly in chemical engineering.

The trends of S-curve evolution and of increasing dynamization have helped engineers innovate competitive products in the market at lower costs and maximum profits (Rahim et al., 2015).

The biggest difference between TESE and other forecasting methods, particularly data science analytics, is the type of distribution used in engineering system development (Zakharov, 2004). As TESE is based on experiential and heuristic changes in various systems (Kell & Lurie-Luke, 2015; Valeri Souchkov, 2013; Valverde, Nadeau, & Scaravetti, 2017), it helps identify problems and mapped innovative ideas and designs (Alex Lyubomirskiy et al., 2018; Schaper, 2020).

Petrov (2019b) clustered TESE into the two categories shown in Fig. 4: (1) the trends of system organisation, which represent the applicability of new systems, and (2) the trends of system evolution, which depict the enhancements of existing systems (Petrov, 2019b).

The discussion in the following sections of this review is based on Fig. 3.

3. Applications and value added by TESE

This section describes how various studies have applied TESE from the highest level of the hierarchy to the lowest, starting from the main (indicated by black boxes in Fig. 3) to the nine trends (indicated by grey boxes in Fig. 3) and other remaining sub-trends.

The TESE toolkit comprises two processes. The first identifies problems via troubleshooting, ascertaining creative strategies using flow analysis, trimming, and feature transferring among other approaches to anticipate problems before plotting for the circumvention of intellectual property. The second uses problem-solving tools to provide generalised recommendations for high-tech problems (Sergei Ikovento, 2009).

TESE is a fundamental toolkit in the TRIZ methodology as it represents the evolution of every characteristic and configuration of a technical system (Petrov, 2019b). However, multiple studies have concluded that using TESE does not always appear to be sequential or display any mutual correlation. This is because the TESE structure can be applied in a flexible and parallel manner, depending on the requirements of the system (Mašin, 2020; Wismadi, 2020).

Therefore, TESE can be applied in the early phases of problem detection to analyse the main parameters of value (MPV) in the S-curve

Table 2
Uses of current and updated TESE for product development.

Articles ↓	TESE →	S-Curve Evolution	Increasing Ideality (Value)	Transition to the Super-system	Increasing Completeness of System Components	Elimination of Human Involvement	Increasing Degree of Trimming	Optimisation of Flows	Uneven Development of System Components	Increasing Coordination	Increasing Controllability	Increasing Dynamicity
1: Logistic Delivery (Wismadi, 2020)	Examined Technology Evolution	At the 1 st stage	Increase Quality of Service (fast, convenient, cheaper)	Supplier of Goods is Outsourcing		Using IoT Technology to Downstream and Upstream Delivery System	Warehouse is Shrinking, Create IT Application	(Just-in-time) Optimise Information and Money	By Design cloud-based Platform Trim All the Vehicle by Outsourcing to the 3rd Parties		Using Platform	Using Platform
	Ideation	1- Create fully automated logistics and supply chain management 2- Cater e-money or e-banking system 3- Design new interface between interior and exterior of house 4- Connecting all delivery components 5- Building façade with concept of closest distance to the road or public access										
2: Flows in Healthcare (Schaper, 2020)	Current Technology Evolution							Optimise Process				
	Ideation	Sub-Trend: Improve useful flows Sub- Sub- Trend: Increase the conductivity of the flow order of coordination A) Increase conductivity of flow: 1- Automate warehouses 2- Manage storage bins 3- Manage inventories 4- Automate scanning 5- Automate booking system 6- Robots can also transport reagents B) Elimination of grey zones: 1- Optimise stock with warehouse management systems automatically in case of (stock availability, orders, staff notification) 2- Automate flow of material and reagents C) Reduce number of flow transformations: 1- Just-in-time (JIT) delivery for supplier										
3: Flood Protection Systems (I. Mašín, 2020)	Current Technology Evolution											Field System
	Ideation	Sub-Trend: Design dynamization Sub- Sub- Trend: Substance dynamization ((monolithic—one hinge—several hinges—flexible—liquid—gas—field)) Flood protection barrier in the form of high-density bale from tree leaves material.										
4: Sewing Machine (Ghane, Ang, Kadir, & Ng, 2020)	Current Technology Evolution				Suggested an Improvement							
	Ideation	Sub-Trends: Operating agent, transmission, energy source, control system Classify patented based on sub-trends by using NLP techniques.										
5: Drill Machines Wi-Fi System Video Displays Spin Echo Signals	Current Technology Evolution							Elimination of Excesses				
	Ideation	Sub-Trends: Reduce negative effects of harmful/incidental flows Sub-Sub- Trend: Reduce the impact of harmful flows Sub-Sub-Sub- Trend: Eliminate resonance										

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Table 2 (continued)

(O. Abramov, 2020)		Proposed algorithm for identifying and utilising excesses in technical systems.													
6: Xiaomi® smartphone (Jing et al., 2019)	Current Technology Evolution	S-curve Analysis													
	Ideation	Clarify correlation between each evolutionary trend and each stage of the S-curve.													
7: Healthcare (Flohr & Schaper, 2019)	Current Technology Evolution	Number of Tests per Hour	Blood Sugar Measuring Devices	Pipette in Laboratory	Human Labour	Disposable Pipetor Tip	Increasing degree of Information and Digitalisation	Elecsys	Trend of Increasing Specificity	Trend of Individualisation	Biological and Chemical Systems	<p>Trend of increasing specificity of drugs: Aims to avoid or at least limit side effects of drug treatment.</p> <p>Trend of increasing individualisation of the treatment regime: In the evolution of therapeutic modalities in, e.g., oncology drugs have become more specific, targeted, and customised for the patients in the past decades.</p> <p>Trend of increasing sensitivity: This can lead to earlier disease detection and maybe also to less fatality in some cases due to more sensitive tests.</p> <p>Trend of increasing degree of information and digitalisation: Use by physicians to improve diagnosis. Support research on new biomarkers. Increasing information in production.</p> <p>Trend of increasing degree of system completeness: Triggering ideas for digitisation activities in healthcare.</p> <p>Trend of increasing degree of dynamization: improvement of manufacturing processes, diagnostic reagents or therapeutic modalities.</p> <p>Trend of flow enhancement: Flow in healthcare processes.</p> <p>Trend of transition to the super-system: This can help to reduce complexity, save costs, and improve patient experience.</p> <p>Trend of increasing degree of trimming: Trimming chemical and biological systems.</p> <p>Trend of uneven development of system components: Change the core technology of diagnostic or medical systems.</p> <p>Trend of increasing ideality (value): Applies to the patient journey in hospitals, improved diagnostics and better medications.</p> <p>Trend of elimination of human involvement: Human resources must be used as effective as possible although many healthcare systems.</p>			
8: Silver sintering	Current Technology Evolution						Lowest Trimming Values for the Components of “Upper and Lower Ram/Sintering Tool”								

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Table 2 (continued)

<p>(Shyong et al., 2018)</p>	<p>Ideation</p>	<p>Trend of increasing degree of trimming: Sintering tools from Siemens® and Infineon Technologies® should be trimmed or improved to achieve the optimum assembly control.</p>										
<p>9: Agricultural Technology (Ivan Mašin & Petru, 2018)</p>	<p>Current Technology Evolution</p>			<p>Vehicle</p>	<p>Straddle Electric Tractor</p>		<p>Trend of Increasing Ideality (value) is the Driving Force for Engineering System Innovation along the S-curve, as well as Driving Force for Diffusions of Innovations.</p>			<p>Speed-based Coordinated Control of Agricultural Vehicles</p>		<p>Sensor Systems, Robotics, Computational Techniques</p>
	<p>Ideation</p>	<p>Trend of increasing degree of trimming: A hydroponic growth system may be integrated into a programmable system providing for the growth of plants.</p> <p>Trend of transition to the supersystem: Multipurpose agricultural unmanned helicopter as an agent of intelligent agriculture technology.</p> <p>Trend of increasing efficiency of substance, energy, and information flows: Several energy transformations to electric propulsion and battery pack.</p> <p>Trend of increasing coordination: The controller automatically controls the speed of the haul agricultural vehicle.</p> <p>Trend of increasing dynamicity: Development of harvesting robot grippers whose design deviated from hard-to-handle robot hands with rigid fingers to design with flexible fingers or cushioned finger design.</p> <p>Trend of elimination of human involvement: Concept of autonomous tractor (a) and robotic platform.</p>										
<p>10: Knee Exoskeleton (Ang, 2018)</p>	<p>Current Technology Evolution</p>	<p>Stage 2</p>	<p>War Ability</p>	<p>Rehabilitation, IoT</p>			<p>Torsion Spring</p>					
	<p>Ideation</p>	<p>S-Curve evolution: Low weight as the new MPV.</p> <p>Trend of increasing degree of trimming: Torsion spring is removed from the system in the new design.</p>										
<p>11: Human Senses (Cinema movies, Soap, Shower heads....) (Mayer, 2017)</p>	<p>Current Technology Evolution</p>			<p>Human Being</p>						<p>Not Interact by Senses of Human</p>		
	<p>Ideation</p>	<p>Trend of increasing coordination: Suggested sub-trends: Touching (kinaesthetic), hearing (auditory), tasting (gustatory), smelling (olfactory), and seeing (visual)</p> <p>Interaction between a product and its user - a human being - can lead to a forecasting and prediction of an engineering system evolution that is designed to interact with human beings.</p>										
<p>12: Dynamic Voltage Restorer</p>	<p>Current Technology Evolution</p>	<p>Stage 2 Stage 3</p>		<p>Heterogeneity of Integration</p>	<p>Level of Self-Containment</p>		<p>Operation Trimming</p>	<p>Damping</p>		<p>Nesting</p>	<p>No. of State of Control</p>	<p>Substance Function</p>

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Table 2 (continued)

<p>case (DVR) (Mansoor, Mariun, Toudeshki, & Wahab, 2017)</p>	<p>Ideation</p>	<p>Transitional standing is depicted by radar-plots in all trends.</p> <p>S-Curve: MPV= Flexibility, cost, efficiency, complexity/ reliability, size/weight.</p> <p>Trend of transition to the super-system: To improve variety of features, functionality, use of super system resources, reliability / reduce cost/size, weight, waste, losses, system complexity.</p> <p>Trend of increasing completeness of system components: To improve operability, dynamic use.</p> <p>Trend of increasing degree of trimming: To reduce size, system complexity.</p> <p>Trend of optimization of flows, trend of increasing coordination, trend of increasing controllability: To reduce energy size time. To improve dynamic performance, response time.</p> <p>Trend of increasing dynamicity: To improve flexibility, control features, efficiency. to reduce energy, size, cost.</p>											
<p>13: Green Roofs (Mansoor, Mariun, & AbdulWahab, 2017)</p>	<p>Current Technology Evolution</p> <p>Stage 3</p> <p>Stage 2</p>												<p>Multi-Layered</p>
<p>14: Door foam of three- and two-door Refrigerator Design (M. Li, Ming, Zheng, & He, 2017)</p>	<p>Current Technology Evolution</p>						<p>Printed Circuit Board (PCB) Display is Pressure Sensitive</p>						
<p>15: Household Appliance (Christoph et al., 2017)</p>	<p>Current Technology Evolution</p> <p>Stage 2</p> <p>Stage 3</p>		<p>Ventilator</p>										<p>Household-Appliance Working with Water</p>
		<p>Overall, 44 ideas were developed.</p> <p>S-Curve (in Stages 3 &4): Generate new idea.</p> <p>Main parameters of value (MPV): Noise, drying result, water consumption, and speed.</p> <p>Trend of transition to the supersystem:</p>											

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Table 2 (continued)

		<p>Sub-trend of increasing differentiation of parameters: Different number of rotor blades or even a differentiation in form, colour or size of rotor blades.</p> <p>Trend of increasing dynamization:</p> <p>Sub-sub-trend of design dynamization, sub-sub-sub-trend of substance dynamization: To do so, carbon dioxide, dry ice or even ultrasonic could be used. Entirely new technology of this kitchen-appliance.</p>											
	Current Technology Evolution	Stage3		Single Source of Light	OTEC		Exciting Subsystem	Exciting Subsystem			Single Directions		
16: Headlamp System (Rahim & Bakar, 2016)	Ideation	<p>S-Curve:</p> <p>MPV: Performance, safety, reliability, effective, adjustable/flexible, serviceability (distinguish the key problems).</p> <p>Trend of transition to the supersystem: Increases the number of light sources such as a bulb or led.</p> <p>Trend of increasing coordination: Various directions of lights.</p> <p>Trend of decreasing human involvement and Trend of increasing degree of trimming: Reducing the subsystem level (reducing transmission; then energy source; then control system; then decision making).</p> <p>Trend of increasing completeness of system components:</p> <p>Operating Agent: Bulb, Transmission: Wiring system, Energy Source: Electric, Control System: Control system of the light level from the steering</p>											
	Current Technology Evolution										Punching Rod		Rigid Wooden Base Plate
17: Paper Punch (Horst Th. Nähler, 2016)	Ideation	<p>Trend of increasing coordination:</p> <p>Sub-trend of coordination of action: 1D–2D–3D</p> <p>Rod sports a deeper carving, providing a sharper edge for cutting.</p> <p>Trend of increasing dynamization:</p> <p>Using elastic material.</p> <p>In case of the base cover, the use of an electric field to hold/stop the offcut.</p> <p>Increased elasticity like rubber or silicone that wraps around the base plate like a glove and keeps the offcut enclosed even better.</p>											
	Current Technology Evolution												Automotive Bumpers
18: Liquid Bumper Technology (Rahim et al., 2015)	Ideation	<p>Trend of increasing dynamicity:</p> <p>Sub-trend of design dynamization – Sub-trend of substance dynamization:</p> <p>Based on the trends, it shows that there are innovation gaps for bumpers that adopt the concept of powder or liquid to move forward in dynamization trends.</p> <p>“It is necessary for a bumper to deform by absorbing non-fatal low impact force from an external object to protect the car/passenger. However, non-fatal low impact force damages the bumper surface. This needs to be done while keeping the engineering system almost unchanged.”</p>											
19: Wheelchair (Aghamohammadi,	Current Technology Evolution												Power Consumption

(continued on next page)

Table 2 (continued)

Ang, Ng, & Mogharrebi, 2015	Ideation	<p>Trend of increasing dynamicity:</p> <p>Install GPS and an emergency button in wheelchair to aid disabled (as well as patients) who need medical attention.</p> <p>Use solar cell panels.</p>
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for all types of technical innovations. This is because MPV analysis identifies the essential features of a system, the “voice of the product”, which leads to future ideation. For instance, MPV analysis was used to develop the concept of incorporating smart antennas into Wi-Fi systems (Abramov, 2014a, 2014b). Furthermore, visualising the life cycle of a hole puncher in reference to the recommendations of its MPVs, such as user comfort, time saving, and availability, on the S-curve helps forecast the future of the product, changes in its supersystems, and behaviour of its customer base (Gronauer & Naehler, 2016). Similarly, A. Lok (2017) identified the perceived value of target consumers of a Haier® electrical water heater to define its MPVs and predict its future. The conceptual framework proposed by Mansoor, Mariun, and Ismail (2012) uses TESE and the S-curve to identify the correct future innovations to cater for electrical deficiencies, such as power distribution. MPVs also depict the current stage of a product’s development and ascertain the system deficiencies that require new enhancements to address them. Furthermore, changes in MPVs have been recommended within the trend of the S-curve evolution at the innovation target-setting stage and benchmarking studies (Ivan Mašin & Petru, 2018). Chybowska and Chybowski (2019) proposed that, with selected MPVs, the S-curve can assess where a system is in its development. To overcome challenges such as increasing innovation speed and adoption of lean-agile approaches by companies (e.g., Siemens), Hammer and Kiesel (2017) categorised MPVs to improve specific product features that carry commercial value. In another study, improving MPVs, such as productivity, strength, and manufacturing ease, in relation to time was depicted on an S-curve diagram to determine breakthrough developments for green roofs (Mansoor, Mariun, & AbdulWahab, 2017). As every product has its MPVs that determine its stage on the S-curve, i.e., initial adaptation, exponential growth, maturity, stability, and heading for expiration, it helps determine the primary improvements required (Ikovenko, 2004; Alex Lyubomirskiy et al., 2018).

The generated ideas were then filtered following the trend of increasing ideality or value to ensure that the improvements were directed correctly. This can be determined using a mathematical

expression that divides the total benefits by the total cost and damages (Ilevbare, Probert, & Phaal, 2013; Mann, 2003; Rahim & Bakar, 2016). Sub-trends were clustered based on their specific functional contributions to an engineering system and then sorted in an orderly manner to reduce defects, attain perfection, and predict suitable solutions (Nahler & Gronauer, 2015). In general, each cluster can eliminate major contradictions in a system (Souchkov & Mars, 1998). For instance, the trend of transitioning to a super-system inspired innovators to merge the elements of a system with super-systems (Mayera & Bertonecellib, 2019), and the trend of flow enhancement inspired the optimisation of system configurations (Schaper, 2020). Ang (2018) used the trend of increasing the trimming degree to improve knee exoskeletons once it was determined that low weight was a new MPV. This TESE subtrend trims sub-systems, operations, and components that carry the lowest value (Ang, 2018). Increasing dynamicity has been used to increase the flexibility, dynamism, and adaptability of flood protection systems (Mašin, 2020). In conclusion, appropriate solutions can be determined and forecasted by examining sub-trends to identify shortcomings and new perspectives for system development over a period of time.

Note that TESE can be used alone or with other tools, such as the 40 Inventive Principles and algorithm for inventive problem solving (ARIZ) (Ilevbare et al., 2013).

To illustrate the use of TESE by practitioners and researchers, Table 2 displays the trends and sub-trends (highlighted in black and gray boxes in Fig. 3, respectively) that numerous products have used across multiple studies.

The usage of TESE adds value as a thought-provoking system (Sheu & Hou, 2013) or supplementary analysis system (Shyong et al., 2018) that introduces opportunities for inventing and improving engineering systems as well as predicting potential solutions (Aghamohammadi et al., 2015; Nählera & Gronauerb, 2017; Petrov, 2019a), particularly for problems caused by the disruptive technologies of Industry 4.0 (Wisnadi, 2020). TESE can also facilitate progress in decision making to continuously improve manufacturing processes (Hammer & Kiesel, 2017; Mayer, 2017), design optimal concepts (Leonid et al., 2015; Park

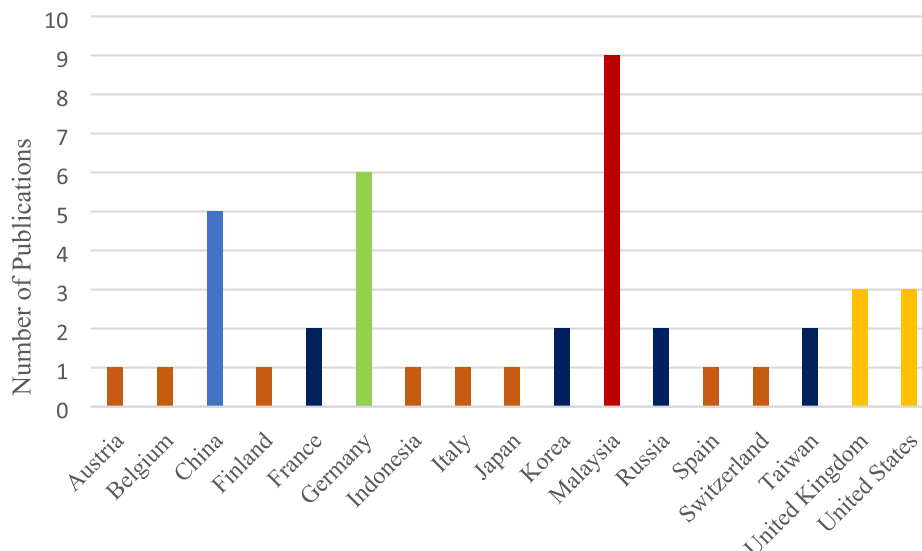


Fig. 5. Distribution of TESE studies according to country of origin.

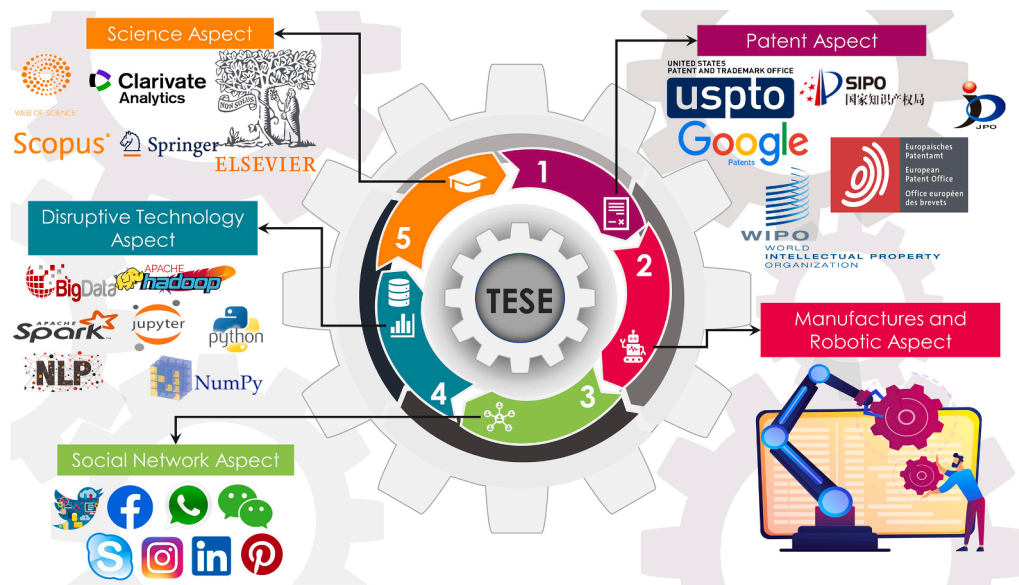


Fig. 6. Integrating TESE with various aspects.

et al., 2013; Schaper, 2020), render significant attributes for innovation purposes (Kell & Lurie-Luke, 2015), counsel recommendations and constructions (Mansoor, Mariun, & Ahmed, 2014), benchmark competitive developments (Ikovenko, 2013), and circumvent patents (Li et al., 2015; Li et al., 2013). In addition, TESE has been shown to perform well when used in a prototype “Create Products” board game and idea generation in the early stages. However, complete details of how players used TESE were not provided (Jantschi et al., 2019).

4. Global acceptance of TESE

TESE originated in Russia and was developed based on the principles proposed by Altshuller. However, unlike TRIZ, TESE has limited reference points because several academic institutions do not offer TESE courses to researchers and practitioners (Ilevbare et al., 2013). To this end, this study conducted a systematic literature review derived from (Barbara Kitchenham et al., 2009) that has been used in various papers published in different fields. A systematic literature review implies the conventional process of identifying, evaluating, and filtering relevant research publications to provide a detailed overview to researchers and scholars (B. Kitchenham & Charters, 2007). To start, the terms “*trend of engineering system evolution*”, “*TESE*”, and “*TRIZ evolutionary trends*” were searched on various academic databases, such as Web of Science™, IEEE Xplore®, Science Direct®, Scopus®, Google® Scholar, Springer®, Wiley, Taylor and Francis, and SAGE®. Only studies published in English between 2009 and March 2021 were included. Approximately 100 publications were compiled using the Endnote® reference manager tool. As the criteria for inclusion in this review included studies that focused on the application of TESE, 42 studies were shortlisted and used as primary studies. The country of origin of these published studies indicates the degree of acceptance of TESE among researchers (Fig. 5). Of the 42 studies, Malaysia ranked first with nine studies published, followed by Germany and China with six and five publications, respectively. Table 2 presents the details of these publications, including trends and sub-trends. Other reviews and studies that discuss TESE with a limited capacity were excluded from this review.

5. Benefits and limitations of TESE

5.1. Benefits of TESE

The TESE toolkit is useful when designing the long-term goals of an

organisation, particularly when identifying which products should be included in the strategic priorities of an organisation. This can be determined by gauging the current stage of each product on the S-curve, i.e., whether the product is at the initial stage of adaptation, undergoing exponential growth, has reached maturity and stability, or heads toward expiration. Furthermore, determining the key products of an organisation as well as its individual product stages allows organisations to outline the commitment of the R&D department in the production line (Teplov et al., 2017; Wang et al., 2010); identify end-of-life products and investment opportunities in disruptive changes (Nahler & Gronauer, 2015); plan strategic product development strategies (Horst Th. Nähler, 2016); forecast technologies and the automation of engineering systems, particularly for agricultural vehicles (Mašín, 2019; Ivan Mašín & Petru, 2018); allocate resources to optimise internal and external factors to deliver goals and decisions (Jing et al., 2019); and reduce complexity, save cost, and identify new features for development, particularly in the healthcare industry (Flohr & Schaper, 2019).

The core strategies of TESE include predicting state-of-the-art omni-tech and omni-innovations (Alex Lyubomirskiy et al., 2018; Petrov, 2019b; Schaper, 2020), which are vital for forecasting new innovations and technologies that align with the strategic priorities of an organisation (Chybowska & Chybowski, 2019; Jing et al., 2019; Ivan Mašín & Petru, 2018). As the TESE toolkit can provide substantial information on future trends and the development of a system, it creates opportunities to enhance existing and new product features if required. As organisations must have a first-mover advantage to obtain a competitive advantage and market share, TESE toolkits can be used to outline future patterns and trends (Christoph et al., 2017; A. Lyubomirskiy et al., 2018; Wismadi, 2020). Therefore, the TESE toolkit is a key device and moving force that businesses can use to competitively stay ahead of the curve (Christoph et al., 2017; Jing et al., 2019; Rahim & Bakar, 2016).

In addition, the use of TESE toolkits for technology forecasting (Ilevbare et al., 2013; I. Mašín, 2020; Rahim & Bakar, 2016) eases the burden of solving complex challenges, such as the innovation of eco-designs (Buzuku & Shnai, 2017), ideas for future household appliances (Christoph et al., 2017), and fixing the deficiencies of an entire or particular piece of equipment (Petrov, 2019b) or system. In addition, TESE encourages organisations to engage in thought processes that produce flexible (Rahim & Bakar, 2016), brisk (Gronauer & Nahler, 2016), replicable (Verhaegen et al., 2009), as well as disruptive and conceivably innovative (Kiesel & Hammer, 2018; Nahler & Gronauer, 2015) ideas to develop solid and reliable solutions (Pham, Vallet, Tyl, &

Pialot, 2018).

In addition to facilitating cost-effective operations (M. Li et al., 2017; Schaper, 2020; Wismadi, 2020), TESE toolkits provide a comprehensive transitional view of product development on radar plots of main trends based on patent knowledge (Mansoor, Mariun, Toudeshki, et al., 2017; Wismadi, 2020) and reduce innovation risks (Jing et al., 2019; Wismadi, 2020). They also help increase product quality (Schaper, 2020), by conducting comprehensive analyses (Petrov, 2019a) at different product stages, boost productivity (Wismadi, 2020) and enable more efficient and effective resource distribution during the production stage.

Although TESE toolkits can be used with other TRIZ tools to improve design processes during product development as well as other processes (Gronauer & Naehler, 2016; M. Li et al., 2015; Schaper, 2020), they can be used independently to achieve the same objectives. Therefore, this yields more enhanced versions of functional and tangible products for use in real-world applications (M. Li et al., 2017; I. Mašín, 2020; V. Souchkov & Mars, 1998).

As shown in Fig. 3, trends and sub-trends were identified by analysing patents, similar to how TRIZ trend evolutions first emerged (Alex Lyubomirskiy et al., 2018; D. L. Mann, 2007). Patent data are core elements of innovation, as they guide future directions and address existing gaps for improvement (Jing et al., 2019; M. Li et al., 2015; Mansoor, Mariun, Toudeshki, et al., 2017). In terms of patent mining, TESE is a practical measure used to visually outline techniques (Wang et al., 2010) and highlight undiscovered system specifications in an objective (Ivan Mašín & Petru, 2018) and quantified manner (Sheu & Chiu, 2017; Yoon & Kim, 2011).

In addition to improving the patent analysis process, TESE is a valuable toolkit for developing patent circumvention strategies (M. Li et al., 2015; M. Li et al., 2017; Rahim et al., 2015). Furthermore, embedding TESE in education benefits both educators and students, as it forms a solid bridge between theory and practice during university-industry collaborations (Zakharov, 2004). The details of the application of TESE in a multitude of different products presented in Table 2 prove that TESE can be used in numerous fields (Kell & Lurie-Luke, 2015). Therefore, the application of TESE in any field can help guide manners of reaching an optimal and ideal state (Mayer, 2017; Pham et al., 2018; Teplov et al., 2017). Table A1 overviews the benefits of applying TESE to various engineering systems.

5.2. Limitations of TESE

Information analysis in the form of patents, scientific articles, customer feedback, and other relevant data were collected as the core of problem solving from the shortlisted studies (Horst Th. Nähler, 2016; Mayera & Bertonecellib, 2019). In particular, TESE considers search and analyses parallel activities (M. G. Lee, Chechurin, & Lenyashin, 2018; Mansoor, Mariun, & AbdulWahab, 2017; Teplov et al., 2017). S. Ikonenko (2013) echoed this sentiment by proposing that leaders and underdogs of innovation are distinguishable based on the strengths and weaknesses of the patents produced. However, as patents are rarely used in the early stages of innovation and invention analysis (M. Li et al., 2017), the extensive amount of patent data available must be manually searched and analysed (H. Park et al., 2013; Valverde et al., 2017). These enormous amounts of patent data are also associated with ever increasing complexity (Wang et al., 2010). Therefore, patent classification must be automated by adopting disruptive Industry 4.0 technologies; such as Big Data analytics (Mayera & Bertonecellib, 2019; Teplov et al., 2017), natural language processing (NLP), and text mining (Yun & Geum, 2020) to overcome these limitations and automate the information acquisition process (Hussmann, 2018). Researchers have struggled to improve TESE by integrating patent analysis with NLP to develop automated methods for identifying technologies. An example of this is the use of KeyGraph for text mining to identify traditional technology evolutionary trends for R&D planning, as explained in Section 2.1 (Wang et al., 2010). Some studies have suggested using the part-of-

speech (POS) tagger of a module to extract adjectives from patents and depict their umbrella properties on an evolutionary potential radar plot to identify the trend phases discussed in Section 2.1 (Verhaegen et al., 2009). As explained in Section 2.2, “adjective + noun” or “verb + noun” forms have been extracted from patents and their semantic similarity to obtain a “reason for jumps” rule base and measured to identify specific trends (Yoon & Kim, 2011). The use of TrendPerceptor, which is based on the property–function approach, has also been examined to identify the trends discussed in Section 2.2 in patents and forecast technologies (Yoon & Kim, 2012). An SAO analysis, which reflects the technological concept of a patent, has been used in conjunction with the evolutionary trends outlined in Section 2.2, to identify promising future patents for floating wind turbines (H. Park et al., 2013). However, these methods focus only on specific trends and cannot be generalised to all trends. Furthermore, updating TESE to the forms seen in Section 2.4, limits its integrability with NLP and Big Data analysis. Therefore, some authors have suggested automating patent classification based on the trend of increasing completeness of system components to overcome this limitation (Ghane et al., 2020).

As TESE trends and sub-trends are broad and general, they provide practitioners and engineers with limited opportunities to use them for specific solutions (Ng, Ang, & Cher, 2018; Savelli, 2016). Therefore, TESE is often integrated with other TRIZ tools (Rahim & Bakar, 2016) or supplemented with an analysis of current patents (Chulvi & Vidal, 2011) to increase its efficacy. The evolution of a TESE system is known to strongly depend on the needs and demands of the community. MPV analysis is then the main activity for S-curve analysis to further accommodate trend analysis (Jing et al., 2019; I. Mašín, 2020). However, despite the importance of this process during trend analysis, most researchers cannot conduct it efficiently because of a lack of access to key information, such as the return on investment of certain systems and applications (Shyong et al., 2018). Moreover, the dataset analysis process, which is crucial because it conveys the preferences of consumers and is used to identify MPVs, is presently labour-intensive and time-consuming. A study that included 8000 respondents concluded that a minimum of six months is required to complete this process (Christoph et al., 2017). The use of fuzzy logic in drilling technologies has been suggested to convert MPVs and obtain crisp outputs on S-curve diagrams that can then be incorporated into decision-making software (Malinin, 2016). In addition, traditional MPV analysis has been suggested to identify adjacent markets for beta-glucan, a biopolymer and food additive, tin cans for food and paint, and batteries (Litvin, 2011) as well as to determine leading demands (Oleg Abramov, Litvin, Medvedev, & Tomashevskaya, 2020). Although this review focuses on the updated versions of TESE (Fig. 3), Table A1 outlines the benefits and limitations of all versions of TESE. As the advantages and limitations discussed in this section remain a critical challenge, they also apply to the updated versions of TESE.

6. Current improvements in TESE

Owing to the benefits and limitations discussed in Section 5, several studies have suggested improvements that can be applied to facilitate the use of trends to help practitioners decipher innovative evolution in engineering systems. For instance, Zouaoua, Crubleau, Choulier, and Richir (2015) proposed a framework that used a model to semantically analyse the first three traditional laws of evolution to effectively facilitate the evolution of a system (Zouaoua, Crubleau, Choulier, & Richir, 2015). An interesting new study combined Polovinkin’s evolutionary rules with patent analysis, which includes searching, selecting, classifying, and presenting the discovery matrix, to enable practitioners to propose hybrid solutions for technology forecasting (Valverde et al., 2017). However, despite multiple efforts to utilise evolutionary trends in a more convenient and expedient manner, numerous challenges remain, such as the severity of human work, time-consuming processes, rigidity to integrate with various pertinent data, failure of practical applications

in different fields of technology, and the incompatibility and non-updatability of methods with modern programming techniques.

As software engineers and researchers constantly progress and evolve, various TRIZ tools have been developed. For instance, multiple studies have used AI algorithms and text mining techniques to classify the technical features of patents and identify the TRIZ level of invention and degree of ideality (Adams & Tate, 2009; Zhen Li & Tate, 2010; Z. Li, Tate, Lane, & Adams, 2012). Another study automated the extraction of technical concepts using text mining methods to visualise them on radar plot diagrams and determine the relevance of patents with evolutionary trends (H. Park et al., 2013). Semantic analysis has been used to depict technological road maps (Zhang, Robinson, et al., 2016) and identify trends in technical development via patent networks (Hyunseok Park, Kim, Choi, & Yoon, 2013; Yang, Huang, & Su, 2018). A combination of TRIZ and NLP techniques has been used to automatically extract inventive information from patent texts and support manufacturing design (Berdyugina & Cavallucci, 2022). Furthermore, AI and an inverse problem graph (IPG) have been integrated to formulate problems in the early phases of inventive lattice structure design (Hanifi, Chibane, Houssin, & Cavallucci, 2022). In addition, Berdyugina and Cavallucci (2022) proposed the automatic extraction of inventive problem-solving information from patents using the inventive design method (IDM) and tracking TRIZ evolutionary trends. Alternative design ideation tools using AI have also been proposed (Chen et al., 2019).

PICC software is a practical example of exploiting TRIZ problem-solving concepts and evolutionary trends to organise all technical knowledge toward the ideality of a system in a consistent pattern (Ondo, 2020). However, despite developments that aim to contribute to evolution trends, no progress yet completely fulfils the usage of trends and sub-trends (Section 3), particularly concerning the details of TESE (Fig. 3). Furthermore, most of the abovementioned methods are based on patent analysis and, in some cases, utilise science-based information that cannot be integrated with other types of data. Section 5.2 discusses the other challenges and limitations.

7. Theoretical contribution for the enhancement of TESE

TESE is a common toolkit in TRIZ and has been used in 44 % of projects for creative ideation (Teplov et al., 2017). By contrast, the trend of increasing completeness of system components in TESE demonstrates the process of analogue-to-digital conversion (Nähler & Gronauer, 2017; Schaper, 2020), which requires TESE to entirely follow this transition process. This is in line with multiple recommendations for the use of automation when examining TESE trends and sub-trends to determine the next innovative product and forecast technologies for designing technical features (Kell & Lurie-Luke, 2015; Ivan Mašín & Petrů, 2018; Verhaegen et al., 2009; Wang et al., 2010). Methods that use visualisation to explore terms and features within TESE are also highly encouraged (Gronauer & Naehler, 2016; Pham et al., 2018). Therefore, integrating TESE with advanced technologies is pivotal (Kiesel & Hammer, 2018; M. Li et al., 2017), such as with AI, machine learning algorithms, and Big Data techniques, to reduce complexity and facilitate the efficient, effective, and rapid analysis of multiple and vast quantities of data (Mayera & Bertoncellib, 2019; Ng et al., 2018; Yoon & Kim, 2012).

This study attempts to address multiple gaps to then make important contribution. First, it extends the limited research on the scope of practical applications of TESE in product innovation. To the best of our knowledge, this study is one of the first to consider ideation through trends and sub-trends of TESE to develop engineering products and forecast new technologies. Second, existing research on TESE has primarily focused on trends or sub-trends in a partial manner. This is one of the earlier studies to examine TESE holistically. Third, the benefits and limitations of TESE within existing publications were assessed. Thus, we outline the reliability of TESE in various innovations. Fourth, to the best of our knowledge, no previous studies have empirically explored the

automation of TESE with computer-aided technologies to facilitate the TESE process. The theoretical contribution of this study is the integration of TESE with computer-aided technologies that support the capability enhancement of TESE for further innovation. Furthermore, this study proposed a framework that integrates the five aspects of TESE (Fig. 6). It comprises four aspects as the input data for further analysis using TESE: (1) scientific information, (2) patents, (3) social networks, and (4) manufacturing and robotics; and one aspect; disruptive technology that acts as the foundation and tool to handle the four input data aspects.

Although many of the studies discussed in this review validate the importance of these five aspects, they have yet to be collectively applied to TESE. Furthermore, more than 100 studies examined in this review did not demonstrate these aspects cohesively. Therefore, the proposed framework assists practitioners in the ideation, development, improvement, and innovation of their products and processes. The details of the proposed framework are as follows.

(1) Scientific Information

Scientific and academic publications are valuable resources for evaluating technical systems using TESE (Teplov et al., 2017). However, conducting quantitative research on science, technology, and innovation (ST&I) to create technology roadmaps (TRM) and identify the R&D gaps that exist between current and emerging or disruptive technologies has always been a challenge (Wang, Fang, & Chang, 2015; Zhang, Chen, & Zhu, 2016; Zhang, Robinson, et al., 2016). Furthermore, incorporating the use of Big Data analytics is integral as ST&I includes various pieces of technological information, and the resources and scientific documents on technology advancement are extensive and ever expanding (Ranaei, Suominen, Porter, & Kässi, 2019; Y. Zhang, Zhang, et al., 2016). However, the present integration of ST&I analysis and TRIZ tools are limited to generic problem solutions (Y. Zhang, Zhou, Porter, & Gomila, 2014). Therefore, assimilating ST&I information with the aid of in-depth layers of TESE can enhance the innovation strategy process, improve system components, and lower risks associated with inventing new products.

(2) Patents

Patents, which are commonly used for classification, citation and information retrieval, and statistical analysis, are a rich resource of technical information that can be used to examine a system based on TESE trends and sub-trends (Chan, Ng, Ang, Ng, & Kor, 2021; Kuang & Weng, 2011; Li, Tate, Lane, & Adams, 2012; Tseng, Lin, & Lin, 2007; Liang et al., 2008). Therefore, consolidating this comprehensive analysis with TESE can reinforce the ideation process, which is vital for product development. Furthermore, transitioning from labour-intensive to automated analyses would increase the efficiency of end-to-end product and process innovations.

(3) Social Networks

Social media is a reliable and emerging resource from which to gather customer feedback to analyse MPVs and apply it to S-curve analysis (A. Lok, 2017; Rahim et al., 2015). The proliferation of social media marketing has significantly increased customer engagement, particularly for luxury brands (X. Liu, Shin, & Burns, 2021). Customer opinions on product features are readily available on social media platforms such as Facebook and Twitter and can be extracted using Big Data mining and NLP (Mars & Gouider, 2017). Furthermore, sentiment analysis on social media provides customers and manufacturers with useful insights into products and services (Shayaa et al., 2018).

TESE begins with the trend of the S-curve evolution, which calculates the MPVs based on time. MPVs represent the “voice of the customer” (VOC) and constitute the preferences and needs of customers, whereas

the “voice of the product” (VOP) comprises the functions and value of a product (Oleg Y Abramov, 2016; Fimin & Smirnova, 2020; Litvin, 2011; Arthur Lok, 2016). Therefore, by compiling the VOC and VOP from social media, product design and development can be based on actual market needs rather than a producer’s assumptions.

(4) Manufacturing and Robotics

Advanced manufacturing has been merged with IoT and Internet communications protocol (ICP) to provide valuable technical information resources for integration with TESE and resolve issues in technical engineering (Ang, 2018; Munirathinam, 2020; Roblek, Meško, & Krapež, 2016). Providing these deliverables is critical (Zheng et al., 2018) by emphasising the use of digital and robotic solutions by incorporating innovative elements of “smartness” and “sustainability” (Ozkeser, 2018) in operating systems worldwide, ranging from smart cities, smart products service based on TRIZ (C. H. Lee, Chen, & Trappey, 2019), and smart manufacturing. For example, a real-time MRI-guided breast intervention robot was developed using TRIZ tools (Y. D. Zhang, Gu, Chen, Yu, & Destech Publicat, 2014). TRIZ tools have been used to modify the tire clamp scheme of car-carrier robots to solve parking problems in cities (Y. Zhang et al., 2019). Furthermore, the trajectory planning, mechanical structure design, and control system of rescue robots have been improved based on TRIZ (Liu, Yang, Tan, & Chen, 2016). Finally, as the COVID-19 pandemic has highlighted the importance of deploying agile and smart solutions, manufacturing and robotics are fundamental in the translation of functional TESE applications.

(5) Disruptive Technologies

As all aspects of input data have the main characteristics of Big Data, which include “*veracity, validity, value, variability, venue, vocabulary, and vagueness*” (Tsai, Lai, Chao, & Vasilakos, 2015), Big Data tools, such as Apache Spark™, provide a user-friendly Python programming interface for multiple analytics and algorithms for machine-learning; NLP; structured query language (SQL) queries; real-time streaming; extract, transform and load (ETL); and graph processing (Alkasem, Liu, Zuo, & Algarash, 2018; Hadoop, 2018). All these would be supportive, cost-effective, and time-saving in TESE analysis. Studies have suggested the use of Big Data techniques to classify patents based on TESE (Ghane et al., 2020). Text mining semantic analysis has been combined with the SAO approach to automate technical development probability within trends (S. Ikovenko, 2013; Yoon & Kim, 2011). Furthermore, text-mining techniques have been used to automate patent classification based on trends to enhance the contribution of TESE (S. Ikovenko, 2000).

When all five aspects are considered, TESE is demonstrated to be a functional and technological roadmap that can be used to strategically and practically improve and innovate engineering systems. These five aspects can be applied individually or collectively to facilitate the application of TESE. They also provide comprehensive and updated technical knowledge and accommodate the extensive analysis of various pieces of information using computer-aided tools. However, conforming to a system with TESE and real-world applications requires additional and supplementary aspects to mitigate the misinterpretation of information, accelerate the speed-to-market, and increase performance. Therefore, the five aspects are supplementary requirements if TESE is to be used effectively and efficiently to elevate the improvement or development of ideation.

The need for an expert to manually apply each trend or sub-trend during patent analysis is tedious and even impossible in cases with large and diversified datasets. Therefore, a concatenated and consolidated application aided by computer software is required to integrate all of these aspects to conform with TESE trends and sub-trends. The fifth aspect, disruptive technologies, is the most important feature that a

programmer can use to compile and analyse the other four aspects based on TESE. Because the automation of TESE with the abovementioned aspects would be state-of-the-art, it warrants serious consideration. Furthermore, any application programmed with disruptive technologies would be capable of collecting all information from the other four aspects. In addition, it would be able to read and analyse all information according to TESE rules, which include MPV selection and S-curve depiction, to then determine a specific trend and identify the “*reason for the jump*” of a specific engineering system. Therefore, automating innovation procedures is important.

8. Conclusion

This review attempted to examine all aspects of TESE, from its initial stage to modern development to the most relevant TESE studies. Emphasis was placed on the key types of development trends and supported by a redrawn illustration of modern TESE to facilitate a better understanding of manners of embracing TESE in creative and innovative design. Discussions by various practitioners and researchers on bridging theory and practice have elucidated how TESE trends and sub-trends eventually lead to ideation and application. Concerning benefits, different uses of TESE have been identified. This includes deciding the strategic priorities of an organisation, as well as technology forecasting and problem solving. Although TESE has been proven useful in generating innovative and compatible ideas, it requires substantial manual assessment, which hampers the realization of effective analyses. A framework that holistically integrates all relevant input data and tools is proposed by weighing the benefits and limitations of TESE.

Our upcoming work on the framework proposed in this review will discuss patent classification based on TESE and aided by machine learning and Big Data techniques. The findings of the review will be further enhanced by discussing MPVs as an imperative activity in the trend of S-curve analysis with the aid of social network analytics. In addition, thorough research on the application of TESE in patent bibliometric, citation, and statistical analyses, as well as the harmonisation of the input data aspects and tools indicated in this article, are recommended for further review.

CRedit authorship contribution statement

Mostafa Ghane: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Mei Choo Ang:** Funding acquisition, Supervision, Writing – review & editing. **Denis Cavallucci:** Writing – review & editing. **Rabiah Abdul Kadir:** Writing – review & editing. **Kok Weng Ng:** Writing – review & editing. **Shahryar Sorooshian:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A.: Overview of the benefits and limitations of TESE

See [Table A1](#).

Table A1
Details, benefits, and limitations of applying TESE in various devices.

Reference	Description	Field of Application and Version of TESE	To be Used and Interpreted by	Future Improvements	Benefits	Limitations
(Verhaegen et al., 2009)	Patent analysis to identify particular trends	Umbrella (Table 1)	Experts	Automating the TESE procedure	Controlled and repeatable measurements of TESE	Manual process
(Wang et al., 2010)	Combined TESE with the visualisation technique of text mining	Patents of magnetic random-access memory (MRAM) systems (Fig. 1)	Semi-automated	Creating an automatic framework to identify evolutionary patterns	R&D planning and allocation of R&D resources	Required experts' effort, manual patent search and collection
(Chulvi & Vidal, 2011)	Compared TRIZ evolution trends with eco-design strategies	LiDS-wheel tool (Fig. 1)	Experts	Conducting patent analysis to identify trends	–	Manual process
(Yoon & Kim, 2011)	Applied NLP techniques to identify trends	Umbrella product family (Fig. 1)	Semi-automated	Making the process fully automated, without human intervention	“Reason for the jump” from one trend to another offers a benefit	Considered only six trends, required manual effort
(Yoon & Kim, 2012)	Automatically extracted properties and functions to analyse trends	Silicon-based thin film solar cells, umbrella (Fig. 1)	Semi-automated	Improving the accuracy of trend identification, other NLP techniques should experience, applying ML techniques	–	Manual measurement and classification, used binary relations only as NLP, limited to six trends, small set of patents
(H. Park et al., 2013)	SAO analysis to identify trends	Floating wind turbines (Fig. 1)	Semi-automated	Extending experiments to more products	–	Not applicable to every technology domain, required experts' effort, not applicable for large patent datasets
(Rahim et al., 2015)	New product development with TRIZ tools	Chemical engineering (liquid bumper technology), updated TESE (Fig. 3)	Experts	Transforming a chemical engineer to a techno-entrepreneur	Developed a unique and competitive product, forecast product, and patent circumvention	Manual patent search and analysis
(Nahler & Gronauer, 2015)	TESE as crucial base of TRIZ	TESE is objective and true for every engineering system, updated TESE (Fig. 3)	Experts	Combining TESE with multiscreen thinking, and function analysis	Used for incremental changes or disruptive changes	–
(Aghamohammadi et al., 2015)	Enhanced wheelchair assistive technology using TRIZ tools and TESE	Wheelchairs (Fig. 3)	Experts	Suggesting assistive functions for wheelchair	TESE can efficiently enhance the functionality of engineering systems	Manual process, general solutions
(Horst Th. Nähler, 2016)	Combined several classic TRIZ tools with TESE and applied nested function models	Paper punchers (Fig. 3)	Experts	Improving the challenges of information gathering, improving the combination of TESE with TRIZ tools	TESE can systematically drive the development of complex engineering systems and idea generation	Manual process, complicated for non-experts
(Rahim & Bakar, 2016)	Technology forecasting using TESE	Automotive headlamp system (Fig. 3)	Experts	The importance of combining several trends to finalise the future system. Should investigate TESE framework for process and service applications	Identified conceptual solutions	Manual process, ambiguous data gathering
(Malinin, 2016)	Applied fuzzy logic to select MPVs	Drilling technologies (Table 1)	Experts	Multiple technologies reported in patents, programmable approach	–	Manual process, focused on trend of S-curve only
(Mansoor, Mariun, Toudeshki, et al., 2017)	Proposed TRIZ-based framework development	Dynamic voltage restorer (Fig. 3)	Experts	Successful conceptual solutions	Conceptual guidance, depicted transitional parameters and trends on radar-plots	Manual process, ambiguous patent knowledge
(Mansoor, Mariun, & AbdulWahab, 2017)	Searched breakthrough solutions with TRIZ tools and TESE	Sustainable green roofs (Fig. 3)	Experts	Useful for patent circumvention and generating multidirectional ideas, distinguishing “jumping the S-Curve”	Generated multidirectional ideas, provided novel prospects	Manual process, ambiguous data gathering and analysis
(Teplov et al., 2017)	Literature review of TRIZ tools, considered TESE as a major tool with 44 % usage	Innovation management	Experts	1- Can apply TESE without use other TRIZ tools, 2- Integration with IT tools	R&D planning, predicted roadmap of product	–
(Christoph et al., 2017)	The trend of increasing dynamization for design	Household appliances (Fig. 3)	Experts	TESE generates ideas with a promising future, overcome barriers (e.g., time, staff, and	Found solutions to problems with TESE	Manual process, hard to find the right information, time consuming

(continued on next page)

Table A1 (continued)

Reference	Description	Field of Application and Version of TESE	To be Used and Interpreted by	Future Improvements	Benefits	Limitations
(M. Li et al., 2017)	Presented a framework for the trimming process	Door foam (Fig. 3)	Experts	resilience) for systematic TESE procedures Integration of TRIZ with other innovation methods	A solid framework, identified the trimming process and key problems	Manual process, included function analysis
(Mayer, 2017)	Interaction of human senses with TESE	Cinema movies, soap, shower heads (Fig. 3)	Experts	Analysing the 3 feelings parameters (like, neutral, and dislike) can be used for future production	Addressed human senses in MPVs	Manual process, ambiguous information gathering
(Ivan Mašín & Petřů, 2018)	Effective innovation engineering procedures in the conceptual design	Agricultural technologies (Fig. 3)	Experts	Applying TESE in engineering systems guarantees a supply of novel ideas, trimming recommendations, and conceptual directions	Described and forecasted the natural transition of engineering systems from one state to another	Manual process
(Shyong et al., 2018)	Applied TRIZ tools and TESE to improve power-module within patents	Silver sintering tools (Fig. 3)	Experts	Using TESE is cost-effective	Achieved an optimum solution	Limited to analysing four patents, manual process, lacked key information
(Ang, 2018)	Applied TRIZ tools and TESE for innovation	Knee exoskeleton (Fig. 3)	Experts	TESE has suggested a few inventive solutions, Big Data makes systems predictive	Trends of increasing degree of trimming improved a system by removing "torsion spring"	Manual process, Big Data analysis not applicable
(I. Mašín, 2019)	Strategic planning based on objective patterns in the development of technical systems	Autonomous agricultural vehicles (Fig. 3)	Experts	Develop significantly in lines with trend of increasing coordination and trend of elimination of human involvement	TESE is powerful tool for innovation and forecasting	–
(Jing et al., 2019)	TESE application roadmap under the strategic development of S-curve	Xiaomi smartphone (Fig. 3)	Experts	The correlation between S-curve and TESE should be clear	Trend of S-curve was used to identify the maturity of technologies and develop strategy for enterprises competition	Difficult to collect and judge patent level, accuracy of stage judgment was challenging, manual process
(Flohr & Schaper, 2019)	TESE in healthcare	Biological, chemical, and mechanical systems, TESE in the healthcare environment	Experts	TESE fosters the "right strategic decisions" and help to forecast promising future technologies	Strategic planning, reduced complexity, saved cost	Manual process
(Chybowska & Chybowski, 2019)	Reviewed TRIZ tools and evolutionary trends	Telephony development, hammer (Table 1)	Experts	TESE can be used individually or with other TRIZ	Predicted the developments and created solutions	–
(O. Abramov, 2020)	Redundancies in engineering systems with TRIZ tools and TESE	Drill machines, Wi-Fi system, video displays, spin echo signals (Fig. 3)	Experts	Identify excessive amounts of energy, substances, and other resources	Increased the success rate of TRIZ innovation projects	Manual process, ambiguous data gathering and analysis, complicated for non-experts
(I. Mašín, 2020)	Applied the trend of increasing dynamicity	Flood protection systems (Fig. 3)	Experts	TESE tools should be more frequently used in engineering systems for problem identification	TESE is objective, increased the flexibility, dynamism, or adaptability	Manual process, ambiguous patent analysis
(Schaper, 2020)	Applied the trend of flow enhancement	Logistic flow in clinical laboratory, e.g., barcoded sample tubes (Fig. 3)	Experts	Trend of increasing degree of system completeness is useful for further digitisation	Provided valuable information and an optimal way for future developments, increased quality, and is cost saving	Manual process, ambiguous function analysis
(Wismadi, 2020)	Used TESE to identify the mechanism of parcel delivery to each house	Housing façade (Fig. 3)	Experts	The trends are not necessarily sequential or mutually dependent	Lowered risk, forecasted future, reduced cost	Manual process
(Ghane et al., 2020)	Integrated NLP and Big Data with TESE	Sewing machine (Fig. 3)	Automated procedure	Experiment on more devices	Required less expert involvement in analysis	Limited to trend of increasing system completeness

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