# Design Science Research Methodology and Its Application to Developing a New Timetabling Algorithm

I Gusti Agung Premananda
*Department of Information Systems*
*Institut Teknologi Sepuluh Nopember (ITS)*
Surabaya, Indonesia
igustiagungpremananda@gmail.com

Aris Tjahyanto
*Department of Information Systems*
*Institut Teknologi Sepuluh Nopember (ITS)*
Surabaya, Indonesia
aristj@its.ac.id

Ahmad Mukhlason
*Department of Information Systems*
*Institut Teknologi Sepuluh Nopember (ITS)*
Surabaya, Indonesia
mukhlason@is.its.ac.id

2022 IEEE International Conference on Cybernetics and Computational Intelligence (CyberneticsCom) | 978-1-6654-9742-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/CYBERNETICSCOM55287.2022.9865661

*Abstract*— **Natural science research is the most common and widely used research methodology. Various fields such as physics, biology, social and behavioral apply this research methodology. However, not all research is suitable for using the natural science research methodology in computer fields such as information technology, computer science, and information systems. Research that aims to solve problems by developing an artefact is more suitable for using the design science research methodology. Unfortunately, there are still many researchers who do not understand or even do not know this methodology. In this paper, we discuss the design science research methodology framework to reintroduce this methodology. The discussion starts with the theory of design science research, which explains five stages, from the explicated problem to the evaluation stage. Furthermore, an example of the application of this methodology is presented for the timetabling problem. This application example shows how the design process was and what the results were. This paper is expected to provide knowledge to researchers, especially for researchers who should use this methodology.**

***Keywords—Design science research, Natural Science Research, Algorithm, Methodology, Timetabling***

## I. INTRODUCTION

Natural science research is research conducted to understand the existing reality. Natural science research has two main activities, namely discovery and justification[1]. Discovery is the process of seeking scientific claims in the form of theories or even laws. Meanwhile, justification is an activity to validate claims that have been found scientifically. The natural science research process has the following methodologies: problem definition, literature review, hypothesis development, data collection, analysis, results, and discussion[2]. Natural science research has been widely applied in various fields such as physics, biology, social, and behavioral.

Natural science research has been carried out in various studies. However, in research in computer fields such as information technology, computer science and information systems, natural science research methodology is not suitable to be applied due to differences in objectives[1]. Natural science research aims to prove a hypothesis through data collection, analysis, and conclusion[3]. In contrast, research in the field of computers aims to produce a tool that can help the goals of humans[4]. For example, social media was created and developed to make it easier for humans to communicate. New algorithms were created to help humans solve their problems. Because of this problem, research methodology other than natural science research is needed.

Currently, there is an appropriate methodology to solve the problem, a methodology that emerged in the 1960s and developed rapidly in the 1980s called design science research[5]. Design science research focuses on developing artefacts to solve existing problems[6]. This methodology departs from a general problem, looking for artefact needs, developing artefacts, deploying, and evaluating. Unfortunately, this methodology is still not known by many researchers. There are still many researchers, especially students, who complete their final project by imposing natural science research or just copying the methodology from the finished final project without knowing why we should use that methodology.

Because of the importance of design science methodology to know and apply in a research environment that focuses on the development of artefacts, this paper reintroduces the steps of research using design science methodology and examples of its application. It is intended that researchers in the form of students and lecturers can use the design science methodology in developing technological research. So that in the future, the research carried out has used the right methodology.

## II. DESIGN SCIENCE RESEARCH

In the design science methodology, there is still no agreed standard form. Various sources have each version, such as Peffers et al. [7], which discusses design science in 6 stages, and Wieringa[8] and Johannesson & Perjons[9] discuss design science in 5 stages but in different terms. However, if examined further, there are no striking differences between the various versions. This paper used the discussion of design science written by Johannesson & Perjons in a book entitled "An Introduction to Design Science". The reason used this book because based on our assessment, the explanation in this book is the easiest version to understand, especially for people new to design science methodology.

### A. Framework for Design Science

In the book written by Johannesson & Perjons, design science is divided into five stages, namely explicated problem, define requirements, design and develop artefacts, demonstrate artefacts, and evaluate artefacts. The output of each stage will be the input for the next stage. Each stage will select and implement appropriate strategies and methods to carry out each stage. In addition, there is knowledge such as theory, research literature, white papers, and information from stakeholders, which is used as material to support each stage. Figure 1 shows an overview of the design research framework.

In its application, most of the activities will not be carried out in detail. Most studies prefer to focus on one or two stages. While other stages can be taken from previous research. Based on the research focus, it is possible to divide it into five types, namely:

- Problem-Focused Design Science
- Requirements-Focused Design Science Research
- Requirements- and Development-Focused Design Science Research
- Development- and Evaluation-Focused Design Science Research
- Evaluation-Focused Design Science Research

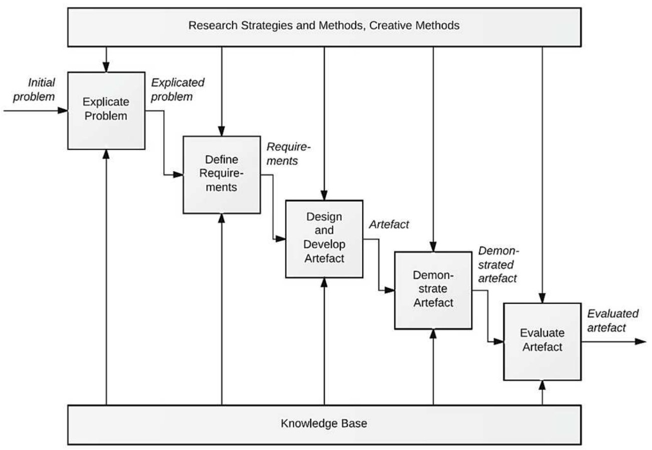


Fig. 1. The method framework for design science [9]

### B. Explicate Problem

The Explicate problem is the first stage of the design science methodology. This stage starts from the input in the form of initial problems that are still not too clear. This input will be processed through three stages:

- Define precisely: this stage will clarify the initial problem to become more focused and reduce the possibility of different interpretations.
- Position and justify: this stage clarifies the position of this problem by identifying what kind of practitioners are affected by this problem. In addition, this stage also justifies why this problem is important to solve.
- Find root causes: this stage focuses on finding the root causes of the existing problem.

Several strategies or research methods can be chosen in carrying out these three stages, such as surveys, case studies, action research, ground theory, ethnography, interviews, focus groups, questionnaires, observations, and documents. The selection of the method is adjusted between the advantages and disadvantages of the method with the existing problems. Some resources can also support these three activities: previous research, newspaper articles, white papers, and stakeholder information. Figure 2 shows an overview of the explicate problem stage.

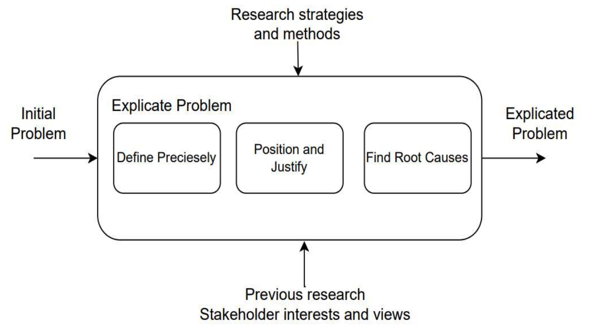


Fig. 2. Activity Explicate Problem

### C. Define Requirements

The requirements definition stage is the stage that defines what requirements must be in the artifact to be developed. The input from this stage is in the form of output from the explicate problem stage, especially at the root causes of the problem. In general, this stage carries out two activities consisting of:

- Outline artefact: this stage determines what type of artifact should be developed (Constructs, Models, Methods, or Instantiations).
- Elicit requirements: this stage translates the root of the problem into a requirement.

The strategy or research method and resources used to carry out these two activities are the same as the methods and resources in the explicate problem stage. Figure 3 shows an overview of the define requirements stage.

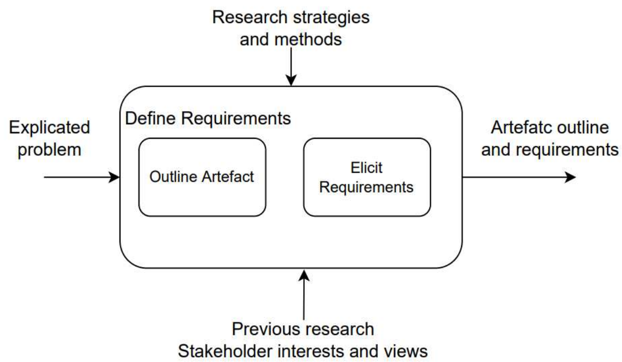


Fig. 3. Activity Define Requirements

### D. Design and Develop Artefact

After the requirements are identified, the next step is to design and develop the artefacts. This stage will carry out four activities:

- Imagine and brainstorm: this stage is done to form ideas that can meet the requirements.
- Assess and select: this stage evaluates the collection of ideas that have been formed, and the best ideas will be selected to be developed at the next stage.
- Sketch and build: this this stage develops the selected idea by translating the idea into a design and building on the design.
- Justify and reflect: at this stage, the designers justify the design decisions made and reflect on them to better prepare for future design and development.

The strategies or research methods that can be used at this stage are: This strategy or research method is not a critical thing but rather a choice to be applied or not. This stage focuses on producing artefacts that can fulfill all requirements, and the method can help generate more ideas. As for resources, previous research and artefacts can be used as a basis for starting to develop artefacts. Figure 4 shows an overview of the design and development artefact stage.

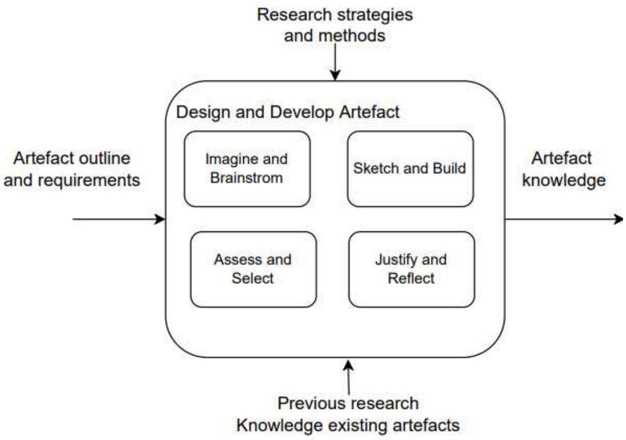


Fig. 4. Activity Design and Develop Artefact

### *E. Demonstrate Artefact*

The demonstration stage aims to prove that the artefacts that have been developed will be able to work on existing problems. This stage has two activities, namely:

- Choose or design case: In this stage, choose and design what kind of case will be used for the artefact demonstration.
- Apply artefact: apply the artifact to the selected case.

The strategy or research method that can be used depends on the selected case. For real cases, generally use action research and case studies. Meanwhile, for fictitious cases, experimental methods are generally used. Meanwhile, the resource that can be used is access to demonstrate the artifact in the selected case. Figure 5 shows an overview of the demonstrate artefact stage.

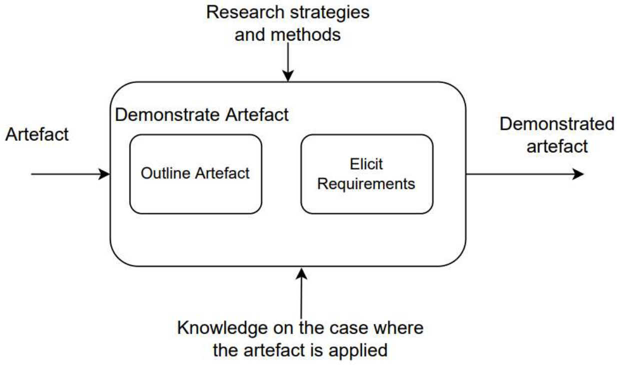


Fig. 5. Demonstrate Artefact

### *F. Evaluate Artefact*

The evaluation stage shows how well the artefacts developed to solve the explicated problem and meet the defined requirements. The evaluation stage has three activities:

- Analyse context: determine the context, which is generally in the form of limitations in conducting evaluations such as limitations on resources, time, people, costs, Etc.
- Select goal & strategy : this activity determines the goal of the evaluation, such as effectiveness in solving the explicit problem, the suitability of the artefact with requirements, comparing the artefact with existing theories, comparing the artefact with other artefacts, and investigating the side effects of implementing the artefact.

  After determining the goals, the next step is to choose the strategy used. The strategy at the evaluation stage is divided into two types: ex-ante vs. ex-post and naturalistic vs. artificial. Ex-ante is a strategy to evaluate artefacts without having to be applied first or without having to be fully finished. In contrast, ex-post is an evaluation that requires the artefact to be applied first. At the same time, the naturalistic strategy is a strategy to apply artefacts to the real world. While artificial is the opposite, applying the artefact to an artificial state. These four strategies have advantages and disadvantages, as shown in table 1. The choice of strategy will affect the method used. Table 2 shows the relationship between strategy selection and what methods can be used.

- Carry Out Evaluation: This stage details the evaluation based on selecting strategies and methods. After that, the evaluation is carried out.

Resources that can be used to support this support on the chosen strategy. Ex-ante and artificial strategies can require expert resources. Meanwhile, ex-post and naturalistic require resources in the form of several sites where artefacts can be used. Figure 6 shows an overview of the evaluate artefact stage.

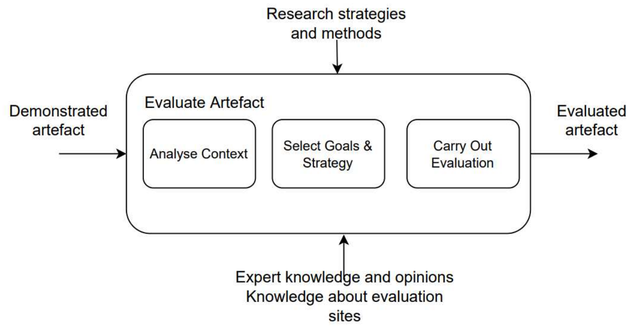


Fig. 6. Evaluate Artefact

TABLE I. CHARACTERISTICS OF EVALUATION STRATEGIES

| | | Ex ante | Ex post |
|---|---|---|---|
| | | Formative evaluation Lower cost Faster Evaluate design or prototype Less risk to participants Higher risk of false positive | Summative evaluation Higher cost Slower Evaluate instantiation Higher risk to participants Lower risk of false positive |
| Naturalistic | Many stake holders Socio-technical artefact Higher cost Slower Organisational access needed Effectiveness Higher external validity Higher risk to participants Lower risk of false positive | Real users, real problem, somewhat unreal artefact Low-medium cost Medium speed Low risk to participants Higher risk of false positive | Real users, real problem, real artefact Highest cost Slowest Identification of side effects Highest risk to participants Lowest risk of false positive |
| Artificial | Few stakeholders Technical artefact Lower cost Faster Efficacy Higher internal validity Less risk to participants Higher risk of false positive | Unreal users, problem, and artefact Lowest cost Fastest Lowest to participants Highest risk of false positive regarding effectiveness | Unreal users, unreal problem, and real artefact Medium-high cost Medium speed Low-medium risk to participants |

TABLE II. RELATION RESEARCH STRATEGY AND METHOD IN EVALUATION STAGE

| | Ex ante | Ex post |
|---|---|---|
| Naturalistic | Action research Focus group Interview | Action research Case study Ethnography Phenomenology Survey Focus group Participant observation |
| Artificial | Mathematical or logical proof Computer simulation Lab experiment Informed argument | Mathematical or logical proof Computer simulation Role-playing simulation Lab experiment Field experiment |

## III. APPLICATION OF DESIGN SCIENCE RESEARCH IN DEVELOPING ALGORITHM

This chapter provides an example of how design science research can use as a methodology for developing an algorithm. The development of an algorithm aims to solve existing problems. Therefore the algorithm can be classified as an artifact. Johannesson & Perjons also classify algorithms as artefacts with a type of method[9]. Based on this, the design science research methodology is suitable for algorithm development research.

The initial problem with education timetabling is that it is challenging to develop a schedule that can adapt to the resources and meets stakeholder interests. Solving timetabling problems manually is very difficult, especially if the problem is immense. On the other hand, automatic scheduling is possible with today's computing usage. However, until now, there is no automatic schedule capable of compiling a schedule that can meet all stakeholders. From this initial problem, the stages of design science research are applied in sections A-E.

### *A. Explicate Problem*

Stages of explicate problems using the document method by conducting a literature review on previous research studies. The literature review is carried out to run three activities in the explicate problem stage:

- Define Precisely: based on some literature[11]–[13], this problem can be focused on and clarified as a difficulty in compiling a schedule that can meet as many soft constraints as possible and still maintains a feasible schedule condition by not violating hard constraints. Hard constraint means constraints that should not be violated. Soft constraint means constraints that can be violated, but it will reduce the quality of the schedule.
- Position and Justify: timetabling problems in the education sector are experienced by universities or schools. The result of the study literature found that this problem has been found in universities in China [14], Egypt [15], and schools in Brazil [16]. The International Timetabling Competition 2019 has collected and published real timetabling course problems from 10 universities in the USA, Czech, Poland, and turkey. Another literature found that student academic can be affected by the construction of timetables [17]. The result of the study literature shows that the problem is a general problem and essential to be resolved.
- Find Root Causes: Based on existing research [13], [18], [19], two root causes exist in the current algorithm:
    - Balancing global and local exploitation in the search space to converge to the best solution.
    - Difficult to determine the number of iterations because there is no guarantee that the solution found is the best.
    - Hard to find the best parameter settings for different case studies to produce the best solution.
    - Existing algorithms only produce good solutions in the case studies understudy

### B. *Define Requirements*

At this stage, the root of the problem is translated into a list of requirements. Document method by conducting a literature review is used to find all requirements. The literature review is applied to two activities, namely:

- Outline artefact: Timetabling problems require a list of procedures that can build a feasible and optimize schedule. The artefact that must be developed is an algorithm.

- Elicit requirements: based on the root cause of the explicated problem and several studies [13], [18], [19], an algorithm should develop with requirements:
  - Algorithm that can balance the exploration and exploitation stages for the case studies that want to be solved.
  - Algorithm that has an adaptive rule to stop iteration when a solution seems to be optimum.
  - Algorithms that require little or no parameter setting
  - Algorithms that have operators to modify solutions that are adaptive to problems.

### C. *Design and Develop Artefact*

The first step is to find ideas through the brainstorming process. This process generates ideas without further analyzing the likelihood of success and how they will be implemented. In the timetabling problem, some ideas may arise, such as adapting an optimization algorithm that has never been applied to the timetabling problem, developing an entirely new algorithm, modifying an existing population or local search algorithm, modifying the neighborhood selection process, and creating new operations neighborhood.

After a set of ideas appears, then in the second stage, the ideas will be assessed and selected. The selection process will see the probability of success of an idea in solving the explicated problem and the possibility that the idea can be developed. For example, modifying the population algorithm has the possibility of not being able to solve the explicated problem because the size of the problem is too large. Various studies have started to abandon this idea in timetabling problems because of the large amount of memory and time required. So, this idea is less likely to be selected.

In the next stage, the ideas that have been selected will be sketched by forming a flowchart and pseudocode. Then the coding process will be run to build the algorithm. The last stage is to justify and reflect by looking back at the reasons and justifications behind design decisions, alternative decisions considered, and the arguments leading to the decisions.

### D. *Demonstrate Artefact*

The algorithm is demonstrated in several case studies to see if the algorithm can run against the explicated problem. There are three case studies selected. Two case studies were chosen based on their popularity and widely used by many researchers, namely the international timetabling competition 2007 and the international timetabling competition 2011. One other case study was selected based on the latest case study, the international timetabling competition 2019. The algorithm developed will be applied to the three case studies ten times on each dataset to see the best value, mean and standard deviation.

### E. *Evaluate Artefact*

The first stage in the evaluation is to find the evaluation context in the form of limitations as a basis for choosing a strategy. The only limitation at this stage of the evaluation is the time limit. However, this limitation is not so strict that it does not prevent the implementation of any strategy.

The second stage is to determine goals, strategies, and methods. The purpose of this evaluation is to see the ability of the developed algorithm to solve the explicated problem, define requirements, and compare it with other artefacts. The first strategy chosen was ex-post. This strategy was chosen because the scheduling problem requires the artifact to be complete and applied directly to the problem. The second strategy chosen is naturalistic. The strategy was chosen because there is already a real-world dataset that can be used as evaluation material. Because the two strategies chosen are ex-post and naturalistic and the availability of real-world datasets, the method used is a case study.

The last stage is to run an evaluation by applying the algorithm to the existing case study. The results of this stage will determine whether the developed algorithm can solve the explicated problem, fulfill the requirements, and produce a competitive solution against other artefacts.

## IV. CONCLUSION

The main objective of this paper was to introduce design science research methodology for research in computer fields such as information technology, computer science, and information systems that are not familiar with this methodology. In this paper, we discuss the five stages of the design science research methodology: explicate problems, defined requirements, design and develop artifacts, demonstrate artifacts, and evaluate artefacts. At each stage, the activities that must be carried out are discussed, the choice of strategies and methods, the possible resources to use, and each stage's inputs and outputs. Finally, this paper illustrates how to apply a science research design methodology to the timetabling problem. From this paper, it is hoped that researchers who focus on developing artefacts to solve existing problems can use the correct methodology.

## REFERENCES

[1] S. T. March and G. F. Smith, “Design and natural science research on information technology,” *Decis. Support Syst.*, vol. 15, no. 4, 1995, doi: 10.1016/0167-9236(94)00041-2.

[2] G. L. Geerts, “A design science research methodology and its application to accounting information systems research,” *Int. J. Account. Inf. Syst.*, vol. 12, no. 2, 2011, doi: 10.1016/j.accinf.2011.02.004.

[3] S. E. Toulmin, “The evolutionary development of natural science.,” *Am. Sci.*, vol. 55, no. 4, 1967, doi: 10.2307/j.ctv1jk0jrs.27.

[4] J. R. Venable, J. Pries-Heje, and R. Baskerville, “Choosing a Design science research methodology,” 2017.

[5] N. Cross, “Science and design methodology: A review,” *Research in Engineering Design*, vol. 5, no. 2. 1993, doi: 10.1007/BF02032575.

[6] J. Q. Azasoo and K. O. Boateng, “A Retrofit Design Science Methodology for Smart Metering Design in Developing Countries,” 2015, doi: 10.1109/ICCSA.2015.23.

[7] K. Peffers, T. Tuunanen, M. A. Rothenberger, and S. Chatterjee, “A design science research methodology for information systems research,” *J. Manag. Inf. Syst.*, vol. 24, no. 3, 2007, doi: 10.2753/MIS0742-1222240302.

[8] R. J. Wieringa, *Design science methodology: For information systems*

*and software engineering*. 2014.

[9] P. Johannesson and E. Perjons, *An introduction to design science*, vol. 9783319106328. 2014.

[10] C. C. Gotlieb, “The construction of class-teacher time-tables,” *Proc. Int. Fed. Inf. Process. Congr. 1962 (IFIP 1962)*, 1963.

[11] M. C. Chen, S. N. Sze, S. L. Goh, N. R. Sabar, and G. Kendall, “A Survey of University Course Timetabling Problem: Perspectives, Trends and Opportunities,” *IEEE Access*, vol. 9, pp. 106515–106529, 2021, doi: 10.1109/ACCESS.2021.3100613.

[12] J. S. Tan, S. L. Goh, G. Kendall, and N. R. Sabar, “A survey of the state-of-the-art of optimisation methodologies in school timetabling problems,” *Expert Syst. Appl.*, vol. 165, p. 113943, Mar. 2021, doi: 10.1016/j.eswa.2020.113943.

[13] A. Bashab *et al.*, “A systematic mapping study on solving university timetabling problems using meta-heuristic algorithms,” *Neural Computing and Applications*, vol. 32, no. 23. 2020, doi: 10.1007/s00521-020-05110-3.

[14] M.-X. Zhang, B. Zhang, and N. Qian, “University course timetabling using a new ecogeography-based optimization algorithm,” *Nat. Comput.*, vol. 16, no. 1, pp. 61–74, Mar. 2017, doi: 10.1007/s11047-016-9543-8.

[15] E. A. Abdelhalim and G. A. El Khayat, “A Utilization-based Genetic Algorithm for Solving the University Timetabling Problem (UGA),” *Alexandria Eng. J.*, vol. 55, no. 2, pp. 1395–1409, Jun. 2016, doi: 10.1016/j.aej.2016.02.017.

[16] L. Saviniec and A. A. Constantino, “Effective local search algorithms for high school timetabling problems,” *Appl. Soft Comput.*, vol. 60, pp. 363–373, Nov. 2017, doi: 10.1016/j.asoc.2017.06.047.

[17] S. Larabi-Marie-Sainte, R. Jan, A. Al-Matouq, and S. Alabduhadi, “The impact of timetable on student’s absences and performance,” *PLoS One*, vol. 16, no. 6 June, Jun. 2021, doi: 10.1371/journal.pone.0253256.

[18] C. K. Teoh, A. Wibowo, and M. S. Ngadiman, “Review of state of the art for metaheuristic techniques in Academic Scheduling Problems,” *Artif. Intell. Rev.*, vol. 44, no. 1, pp. 1–21, Jun. 2015, doi: 10.1007/s10462-013-9399-6.

[19] S. A. Mirhassani and F. Habibi, “Solution approaches to the course timetabling problem,” *Artif. Intell. Rev.*, vol. 39, no. 2, pp. 133–149, Feb. 2013, doi: 10.1007/s10462-011-9262-6.