

Uncertainty-wise Test Case Generation and Minimization for Cyber-Physical Systems

A Multi-Objective Search-based Approach*

Man Zhang, Shaukat Ali and Tao Yue

Abstract— Cyber-Physical Systems (CPSs) typically operate in highly indeterminate environmental conditions, which require the development of testing methods that must explicitly consider uncertainty in test design, test generation, and test optimization. Towards this direction, we propose uncertainty-wise test case generation and test case minimization strategies that rely on test ready models explicitly specifying subjective uncertainty. We propose two test case generation strategies and four test case minimization strategies based on Uncertainty Theory and multi-objective search. These strategies include a novel methodology for designing and introducing indeterminacy sources in the environment during test execution and a novel set of uncertainty-wise test verdicts. We performed an extensive empirical study to select the best algorithm out of eight commonly used multi-objective search algorithms, for each of the four minimization strategies, with five use cases of two industrial CPS case studies. The minimized set of test cases obtained with the best algorithm for each minimization strategy were executed on the two real CPSs. The results showed that our best test strategy managed to observe 51% more uncertainties due to unknown indeterminate behaviors of the physical environment of the CPSs as compared to the rest of the test strategies. In addition, the same test strategy managed to observed 118% more unknown uncertainties as compared to the unique number of known uncertainties.

Index Terms— Uncertainty, Cyber-Physical Systems, Test Case Generation, Test Case Minimization, Multi-Objective Search, Uncertainty Theory.



1 INTRODUCTION

Given the fact that uncertainty is inevitable in Cyber-Physical Systems (CPSs) [7], classical testing methods (e.g., regression testing [8], conformance testing [11, 12]) must be extended to explicitly consider uncertainty. There exist a few methods in the literature that explicitly take uncertainty into account while designing methods for testing CPSs [14, 15]. We present, in this paper, one such work but particularly focus on uncertainty-wise test case generation and minimization.

Our test case generation and minimization approaches are model-based, in the sense that these rely on test ready models explicitly specifying *subjective* uncertainty, which is defined as “lack of knowledge” [17, 18] about the expected behavior of a CPS in the presence of uncertainty in its operating environment. Such test ready models are developed with the Uncertainty Modeling Framework (UncerTum) [19, 20], which defines a set of UML Profiles (e.g., the UML Uncertainty Profile (UUP)) and model libraries. With UncerTum, one can create test ready models, called *Belief Test Ready Models* (BMs), which are composed of two types of UML diagrams: 1) *Belief Class Diagrams* (BCDs) capturing testing interfaces (e.g., observable states and operations to send stimulus) and 2) *Belief State Machines* (BSMs) modeling the expected behavior of a CPS with explicitly captured *subjective* uncertainty. Note that both

BCDs and BSMs are standard UML class diagrams and state machines with stereotypes from UUP applied.

We developed two test case generation strategies, named as *All Simple Paths* (No Loops) and *All Paths with a Fixed Maximum Length* on BSMs. These two strategies are inspired from the ones reported in [21], but are extended for BSMs and considered various uncertainty aspects such as the number of uncertainties in a test path and overall uncertainty of a test path based on Uncertainty Theory [22]. Moreover, we take into account the advanced features of standard UML state machines such as composite states, submachine states, and orthogonal regions. Using the tool developed for our approach, test cases satisfying a selected test case generation strategy can be automatically and systematically generated.

Depending on the complexity of a CPS and a chosen test case generation strategy, the number of generated test cases might be very large. Automatically executing all generated test cases, especially for complex CPSs, is impractical since test execution may require setting up special hardware, simulators, and emulators. Therefore, we need an approach that can minimize the number of test cases to be executed and maximize the coverage of transitions,

- Man Zhang is with Simula Research Laboratory and University of Oslo, P.O.Box 134, 1325 Lysaker, Norway. E-mail: manzhang@simula.no.
- Shaukat Ali is with Simula Research Laboratory, P.O.Box 134, 1325 Lysaker, Norway. E-mail: shaukat@simula.no.
- Tao Yue is with Simula Research Laboratory, P.O.Box 134, 1325 Lysaker, Norway. E-mail: tao@simula.no.

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meanwhile maximizing the following four uncertainty related objectives: 1) the number of uncertainties covered, 2) the number of unique uncertainties covered, 3) the overall uncertainty (computed based on the Uncertainty Theory [22]) of all the selected test cases, and 4) the coverage of uncertainty space (from the Uncertainty Theory [22]). To achieve this, we decided to benefit from the commonly-applied, eight multi-objective search algorithms from the Evolutionary Algorithm, Hybrid Algorithm, and Swarm Algorithm classifications of such algorithms [23]. In addition, we used Random Search (RS) as the comparison baseline. Based on the above four uncertainty related objectives, we defined four uncertainty-wise multi-objective test case minimization strategies, which share the objectives of minimizing the number of test cases and maximizing the transition coverage.

In order to assess the cost-effectiveness of the proposed test case generation and test case minimization strategies, we performed an empirical evaluation using two industrial case studies: GeoSports (GS) [24] (with one use case) and Automotive Warehouse (AW) [25] (with four use cases). Based on the results, we concluded that all the selected multi-objective search algorithms outperformed RS in terms of minimization. In terms of the comparison across the test strategies to discover uncertainties in the behaviors of CPSs, our best strategy managed to discover 51% more uncertainties as compared to the rest of the test strategies due to unknown indeterminacy sources in the physical environments of the two industrial case studies. In addition, the same test strategy observed 118% more unknown uncertainties due to unknown indeterminate behaviors of the physical environments as compared to the already known uncertainties.

The rest of the paper is organized as follows. In Section 2, we briefly summarize UncerTum [20] and the Uncertainty Theory. The overview of the proposed approach is presented in Section 3. In Section 4, we describe details of the test case generation and minimization. The evaluation is discussed in Section 5, followed by the tool implementation (Section 6), related work (Section 7) and conclusion (Section 8).

2 BACKGROUND

2.1 Uncertainty Modeling Framework (UncerTum)

UncerTum [19, 20] was proposed to develop test ready models for enabling Model-based Testing (MBT) of CPSs in the presence of environmental uncertainty. UncerTum is equipped with specialized modeling notations (named as the UML Uncertainty Profile (UUP)) for specifying uncertainties. UUP is the core of UncerTum and UUP implements an uncertainty conceptual model, named as U-

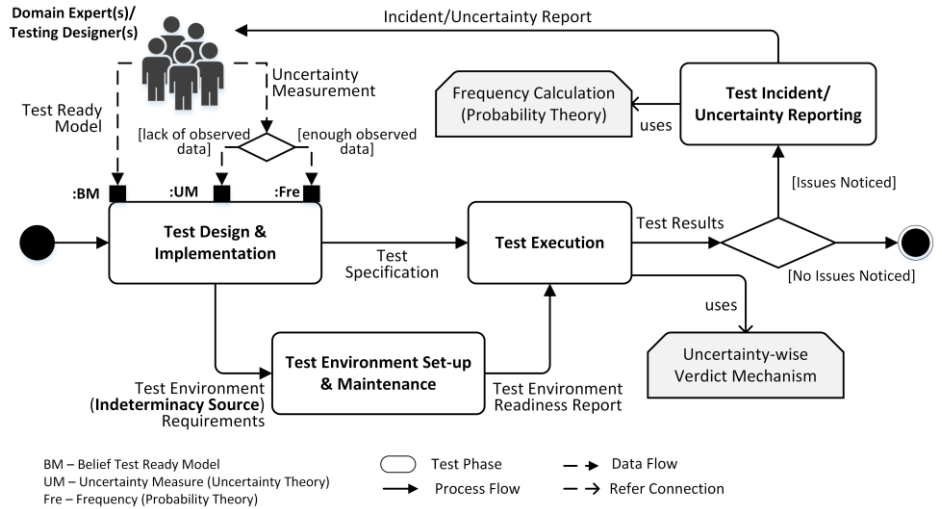


Fig. 1. Overview of the Test Process with UncerTum and UncerTest

Model [26]. U-Model was developed to understand uncertainties in CPSs by defining, characterizing and classifying uncertainties and associated concepts (e.g., *Belief*, *BeliefStatement*, *IndeterminacySource*, *Measure*, and *Measurement*), and their relationships at a conceptual level.

UncerTum additionally defines four sets of UML model libraries: *Pattern*, *Time*, *Measure*, and *Risk* libraries, by extending the existing UML profile: Modeling and Analysis of Real-Time and Embedded Systems (MARTE) [27]. The purpose of defining these libraries is to ease the development of test ready models with uncertainty.

In summary, key UML diagrams used in UncerTum are standard UML state machines and class diagrams with UUP stereotypes and the model libraries applied. Such diagrams all together are referred as BMs in our context. Details of UncerTum with examples can be found in our previous work [19, 20].

2.2 Uncertainty Theory

2.2.1 Probability Theory vs. Uncertainty Theory

Probability Theory is commonly used to measure uncertainty based on a long-run experiment [28]. But in the context of testing, it is quite common that observed data is not ready (i.e., being “close enough to the long-run frequency” [28]) at the initial stage of a test design for enabling MBT, due to, for example, economic reasons and/or technical difficulties [28]. Therefore, *Probability Theory* is not ideal for measuring uncertainty in such a context to guide the four testing phases shown in Fig. 1 (i.e., *Test Design & Implementation*, *Test Environment Set-up & Maintenance*, *Test Execution* and *Test Incident*), although we acknowledge that there exist testing techniques (e.g., [29, 30]) that are built on *Probability Theory*. Notice that these testing phases are well defined in [31].

Uncertainty Theory is an attempt for weakening the prerequisite of applying *Probability Theory* [28]—not having sufficient observed data for developing an uncertainty-wise MBT technique. *Uncertainty Theory* is defined by Liu [22] as “a branch of mathematics for modeling human uncertainty” to deal with uncertainty in the situation of lacking observed data [28]. Notably, *Uncertainty Theory* has been

applied to solve various problems, including optimal control [32], optimal scheduling (the train timetable problem [33]), risk assessment [34] and the maximum flow problem of the network [35]. In *Uncertainty Theory*, uncertainty is considered as the degree of the belief of a belief agent about a particular “thing”, estimated by one or more domain experts (i.e., the belief agent) [22, 28]. This definition well fits the situation in the test design phase. Notably, our definition of uncertainty in U-Model [26] conforms to this definition, on which the uncertainty modeling framework (UncerTum) was proposed. Therefore, our testing technique UncerTest being presented in this paper is established on *Uncertainty Theory*.

2.2.2 Integrating Uncertainty to Testing Phases

As shown in Fig. 1, at the *Test Design & Implementation* phase, *Uncertainty Theory* is used as part of the UncerTum framework for specifying and measuring the uncertainty of behaviors of a CPS and the environment of its execution. In the *Test Environment Set-up & Maintenance* phase, indeterminacy sources (one important concept associated with uncertainty, Section 4.3.1) is introduced to the test environment. *Uncertainty-wise Verdict Mechanism* (Section 4.3) is used in the *Test Execution* phase to produce test results and *Frequency Calculation*, which is based on Probability Theory, is particularly performed at the *Test Incident / Uncertainty Reporting* phase for producing uncertainty reports. In short, to enable uncertainty-wise testing, three out of the four typical testing phases should be tailored for addressing the uncertainty aspect. Note that the framework presented in Fig. 1 is generic in the sense that both *Probability Theory* and *Uncertainty Theory* can be supported in a very similar manner. The only difference is how the uncertainty information of a BM is collected and therefore specified/measured in the BM, in the *Test Design & Implementation* phase.

2.2.3 Summary of Uncertainty Theory

Uncertainty Theory defines a term called *Uncertainty Measure* (UM), which captures a specific uncertainty value (a number) related to an event. This number assigns the *belief degree* [26] of a *belief agent* [26] to the event, for the purpose of indicating her/his confidence about the occurrence of

the event [22]. *UM* is represented as the \mathcal{M} symbol. As Liu suggested in [22], \mathcal{M} respects the following three axioms:

Axiom 1. (Normality) $\mathcal{M}(\Gamma) = 1$, (Γ is the universal set).

Axiom 2. (Duality) $\mathcal{M}\{\Lambda\} + \mathcal{M}\{\Lambda^c\} = 1$, where Λ shows a particular event, whereas Λ^c shows all the elements in the universal set excluding Λ .

Axiom 3. (Subadditivity) $\mathcal{M}\{\bigcup_{i=1}^{\infty} \Lambda_i\} < \sum_{i=1}^{\infty} \mathcal{M}\{\Lambda_i\}$ (every countable sequence of events $\Lambda_1, \Lambda_2, \dots$).

Below, we provide the definition of *Uncertainty Space* and the related theorem, which are relevant to our work. Readers may consult paper [22] for more details about the theory.

Uncertainty Space: A triplet $(\Gamma, \mathcal{L}, \mathcal{M})$, where Γ is the universal set, \mathcal{L} is a σ -algebra [36] over Γ , and \mathcal{M} is *UM*.

Theorem: Let $(\Gamma_k, \mathcal{L}_k, \mathcal{M}_k)$ be uncertainty spaces and $\Lambda_k \in \mathcal{L}_k$, for $k = 1, 2, \dots, n$. Then $\Lambda_1, \Lambda_2, \dots, \Lambda_n$ are always independent of each other if they are from different uncertainty spaces.

3 OVERVIEW

An overview of our approach (named as UncerTest) is presented in Fig. 2. The only input for the test case generation is BMs developed using UncerTum (Section 4). In the test design phase, UncerTest generates abstract test cases from BMs using the *All Directed Paths* strategy [21]. The strategy is configurable and in the context of this paper we configure it to develop two types of strategies: 1) *All Simple Paths* (ASP): A set of all simple paths (no loops) in a BSM, each of which contains unique states and transitions; and 2) *All Paths with Maximum Path Length* (AMP): A set of all paths in a BSM, the maximum length of each of which can be set to any positive number. Each path is an abstract test case.

For each abstract test case, the UncerTest approach automatically calculates *UM*, based on the *Uncertainty Theory* (Section 2.2). Followed by that, it applies the *Uncertainty-wise Test Minimization* approach since the number of automatically generated abstract test cases is typically very large for any non-trivial CPS and it is practically impossible to execute all of them. Test case minimization strategies that UncerTest focuses on can be formulated as multi-objective search problems and thus we opted for multi-objective search algorithms (e.g., NSGA-II) to address these

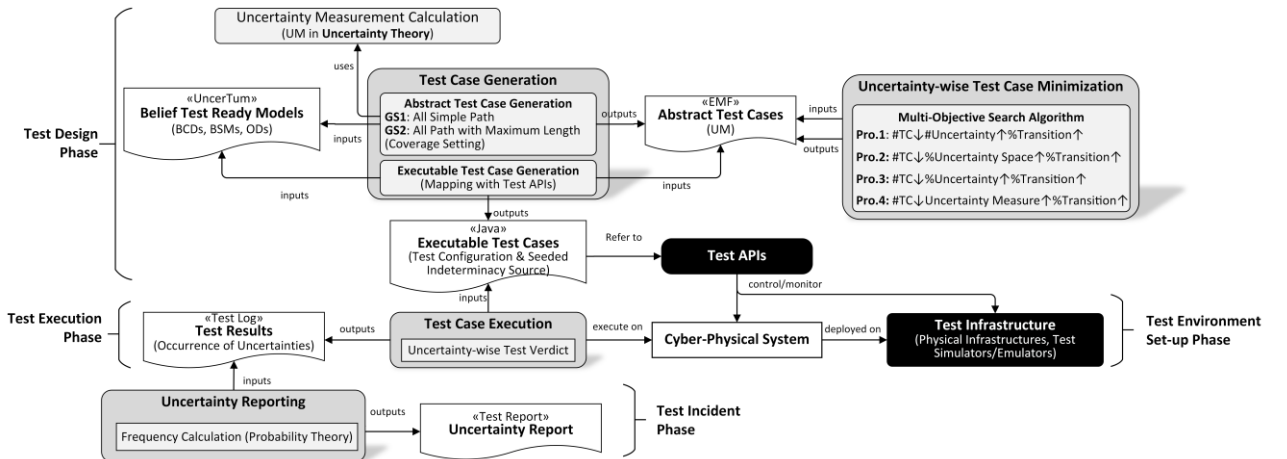


Fig. 2. Overview of UncerTest

problems. All the search problems aim to minimize the number of test cases and maximize the transition coverage, but they distinguish themselves by maximizing one of the following four uncertainty related objectives: 1) The average number of uncertainties covered by the selected test cases; 2) The average percentage of uncertainty space covered by the selected test cases; 3) The average *UM* of the selected test cases; and 4) The average number of unique uncertainties covered by selected test cases. A minimized set of abstract test cases is then converted into executable test cases, which are executed to test a CPS.

As shown in Fig. 2, we also align UncerTest with the four typical testing phases presented in Fig. 1; UncerTest is comprehensive in the sense that it, together with UncerTum, covers all the required aspects of an MBT solution and supports the complete test lifecycle.

4 TEST CASE GENERATION AND MINIMIZATION

In this section, first, we present the test case generation approach of UncerTest (Section 4.1), followed by its test minimization strategies (Section 4.2).

The running example shown in Fig. 3 will be used along the way to illustrate UncerTest. The BSM of the running example has two regions and various elements of the BSM are stereotyped with «BeliefElement» (e.g., the *S2* state). One of the attributes of this stereotype allows specifying *Uncertainty* with the measure of *UncertaintyMeasure* and the actual value of it (i.e., *Measurement*) (e.g., 0.8 specified as part of the stereotype applied on *S2* in Fig. 3).

Section 4.1 presents our test case generation approach; Section 4.2 presents our uncertainty-wise test case minimization approach; Section 4.3 discusses the process of executable test case generation; and Section 4.4 discusses our test execution and reporting mechanisms.

TABLE 1
DEFINITIONS

Def#	Name	Definitions
1	<i>R</i>	Suppose a region of a BSM can be represented as a tuple $R = (is, ST, TR, FS)$, where <i>is</i> is the initial state of <i>R</i> ; $ST = \{st_i \mid 0 < i \leq nst\}$ is the set of states (i.e., simple, choice, submachine, and composite states), each of which may have a UUP stereotype (Section 2.1) applied; $TR = \{tr_i \mid 0 < i \leq ntr\}$ is the set of transitions, which may have UUP stereotypes (Section 2.1) applied; and $FS = \{fs_i \mid 0 < i \leq nfs\}$ is the set of final points (i.e., final state, exit point, and terminate) in <i>R</i> .
2	<i>BSM</i>	A BSM can be viewed as a set of orthogonal regions [2]: $BSM = \{R_i \mid 0 < i \leq nr, \forall R_i \perp \forall R_j \text{ iff } nr > 1, i \neq j\}$. Note that if a state is composite or a submachine, it is equivalent to a state machine.
3 and 4	<i>U</i> and <i>UM(U)</i>	<i>Uncertainty (U)</i> of (st_x, tr_y, st_z) is a situation whereby the belief agent does not have full confidence that st_x transits to st_z through the tr_y transition in the BSM. In Uncertainty Theory, <i>U</i> can be measured by <i>Uncertainty Measure (UM(U))</i> , which is a belief degree ranging from 0 to 1 and is represented as: $UM(st_x, tr_y, st_z) = \mathcal{M}\{(st_x, tr_y, st_z)\}$.
5	<i>USP</i>	<i>Uncertainty Space (USP)</i> of (st_x, tr_y) is a triplet: $USP(st_x, tr_y) = (\Gamma, \mathcal{L}, \mathcal{M})$, where Γ is the universal set that contains all the options (i.e. $(st_x, tr_y, st_{z1}), (st_x, tr_y, st_{z2})$) of transiting from st_x via tr_y , about which a belief agent hold beliefs; \mathcal{L} is a σ -algebra over Γ ; and \mathcal{M} is the uncertainty measure of the elements in \mathcal{L} . For example, as shown in Fig. 3, $UM = \mathcal{M}\{(S1, T2, S2)\} = 0.8$ indicates that the belief agent believes that <i>S1</i> will transit to <i>S2</i> by <i>T2</i> with a probability of 0.8. $USP(S1, T2)$ is $(\Gamma, \mathcal{L}, \mathcal{M})$, where $\Gamma = \{(S1, T2, S2), (S1, T2, S3)\}$; $\mathcal{L} = \{\emptyset, \{(S1, T2, S2)\}, \{(S1, T2, S3)\}, \Gamma\}$; $\mathcal{M}\{\emptyset\} = 0$, $\mathcal{M}\{(S1, T2, S2)\} = 0.8$, $\mathcal{M}\{(S1, T2, S3)\} = 0.2$ and $\mathcal{M}\{\Gamma\} = 1$. The BSM shown in Fig. 3 has three <i>USPs</i> (i.e., $USP_{SM} = \{USP(S1, T2), USP(S7, T8), USP(S8, T9)\}$ and eight <i>UMs</i> : $\mathcal{M}\{S5, T6, S6\} = 1$, $\mathcal{M}\{S6, T7, S7\} = 1$, $\mathcal{M}\{S7, T8, S8\} = 0.9$, $\mathcal{M}\{S7, T8, S9\} = 0.1$, $\mathcal{M}\{S8, T9, S9\} = 0.6$, $\mathcal{M}\{S8, T9, S7\} = 0.4$, $\mathcal{M}\{S8, T10, F4\} = 1$, $\mathcal{M}\{S9, T11, F5\} = 1$.
6	<i>P</i>	A <i>Path (P)</i> in a region is a sequence of states and transitions represented as $P = (e_0, \dots, e_i, \dots, e_{np})$, where e_0 is <i>is</i> (the initial state of the region); e_{np} is an element from <i>FS</i> , $(e_i, e_{i+1}) = \{(st_x, tr_y) \mid i < np, i \text{ is even, } st_x \text{ is the source state of } tr_y\}$; and $(e_i, e_{i+1}) = \{(tr_x, st_y) \mid i < np, i \text{ is odd, } st_y \text{ is target state of } tr_x\}$.
7	<i>UM(P)</i>	<i>Uncertainty Measure of Path (UM(P))</i> $(e_0, \dots, e_i, \dots, e_{np})$ is a belief degree, with which a belief agent believes that e_0 arrives e_{np} by following the sequence of (e_1, \dots, e_{np-1}) . It can be represented as: $UM(P) = \mathcal{M}\{\bigcap_{i=0}^{np-1/2} \{(e_i, e_{i+1}, e_{i+2})\}\}$. An example in Region 2 (Fig. 3) is $\bar{P}_2 = (S5, T6, S6, T7, S7, T8, S8, T9, S9, T11, F5)$, which can be seen as a sequence of $(S5, T6, S6), (S6, T7, S7), (S7, T8, S8), (S8, T9, S9), (S9, T11, F5)$. Along the path, two uncertainty spaces are encountered: $USP(S7, T8)$ and $USP(S8, T9)$. $UM(\bar{P}_2)$ is therefore calculated as $\mathcal{M}\{S5, T6, S6\} \cap \dots \cap \mathcal{M}\{S9, T11, F5\}$. Since each $(st_i, tr_{i+1}, st_{i+2})$ is from different <i>USPs</i> , $UM(\bar{P}_2) = \mathcal{M}\{S5, T6, S6\} \wedge \dots \wedge \mathcal{M}\{S9, T11, F5\} = 0.6$.
8	<i>NU(P)/NUU(P)</i>	The number of <i>Uncertainties (Def3)</i> <i>NU</i> of a <i>P</i> $(e_0, \dots, e_i, \dots, e_{np})$ is the number of uncertainties that appear along the <i>P</i> . Further, <i>NUU</i> represents the number of unique uncertainties in the <i>P</i> . For example, $NU(\bar{P}_2) = NUU(\bar{P}_2) = 2$.
9	<i>US</i>	The number of <i>Uncertainty Spaces (Def5)</i> <i>NUSP</i> in a <i>P</i> $(e_0, \dots, e_i, \dots, e_{np})$ is the number of uncertainty spaces that appear along the <i>P</i> . For example, $NUSP(\bar{P}_2) = 2$.
10	<i>PP</i>	A <i>Parallel Path (PP)</i> is a sequence of <i>Ps</i> represented as: $PP = \{P_i \mid 0 < i \leq npp, \forall P_i \perp \forall P_j, i \neq j\}$.
11	\bar{P}	A <i>Simple Path (\bar{P})</i> is a sequence of unique states and transitions represented as $\bar{P} = (e_0, \dots, e_i, \dots, e_{np})$, where $\forall e_i \neq \forall e_j (i \neq j)$.
12	<i>P'</i>	A <i>Deep Path (P')</i> is a <i>P</i> that does not contain any composite or submachine states, which can be represented as $P' = (e_0, \dots, e_i, \dots, e_{np})$, where $\forall e_i$ is not a composite or submachine state.
13	<i>t</i>	A test case <i>t</i> in a state machine is a <i>deep path (P')</i> , which can be <i>parallel (PP')</i> or <i>simple (\bar{P}')</i> .
14	<i>NU/NUU(t)</i>	<i>NU/NUU</i> in a test case represents the total number of uncertainties/unique uncertainties covered by it, calculated as: $NU(t) = \begin{cases} \sum_{i=0}^{npp} NU(P_i) & t = PP' \\ NU(P) & t = P \end{cases}, UNU(t) = \begin{cases} \sum_{i=0}^{npp} NUU(P_i) & t = PP' \\ NUU(P) & t = P \end{cases}$
15	<i>UM(t)</i>	<i>UM</i> of a test case <i>t</i> is a number, indicating the belief degree, with which a belief agent believes that the test case will be executed successfully. <i>UM</i> is calculated as: $UM(t) = \begin{cases} \bigwedge_{i=0}^{npp} UM(P_i) & t = PP' \\ UM(P) & t = P \end{cases}$
16	<i>T</i>	A test set <i>T</i> is a set of test cases derived from a BSM using a test case generation strategy: $T = \{t_i \mid 0 < i \leq nt\}$.

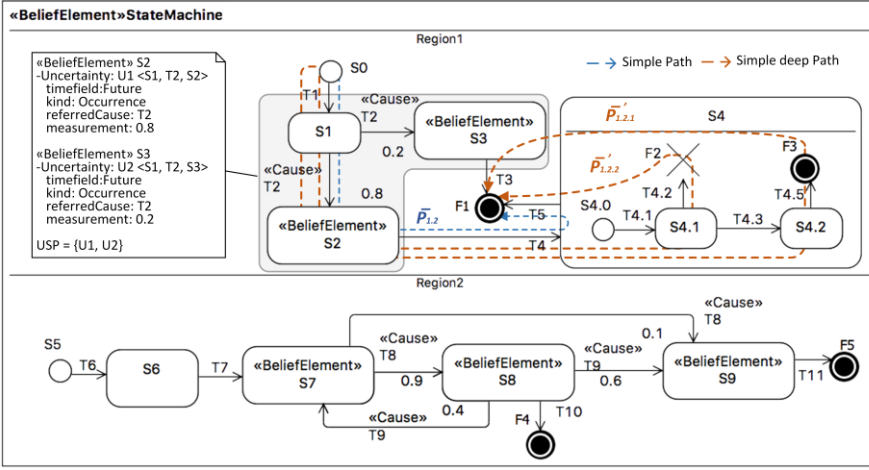


Fig. 3. Belief State Machines (BSMs) of the Running Example

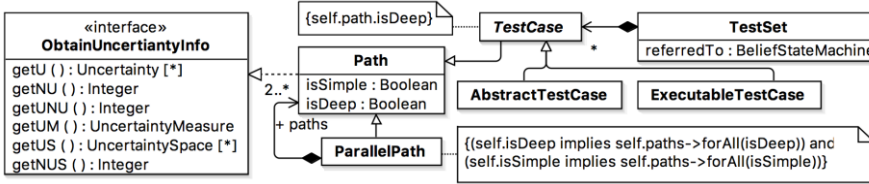


Fig. 4. Key concepts of UncerTest and Their Relationships

4.1 Abstract Test Case Generation

UncerTest automatically generates abstract test cases from BMs, based on the test case generation strategies that are applied on BSMs. In the remaining section, we first provide necessary definitions (Section 4.1.1), followed by the test case generation strategies (Section 4.1.2).

4.1.1 Definitions

To measure uncertainties specified by UncerTum and apply them and their measurements in the testing phase, we formalize related concepts (e.g. *Path*, *UM*) in TABLE 1, and exemplify them with the running example in Fig. 3.

In TABLE 1, we formalized the state machine (BSM), region, states and transitions (Def1 and Def2). To adopt Uncertainty Theory in UncerTest to specify and calculate measurements of uncertainties, we further define *U* (Def3), *UM* (Def4) and *USP* (Def5) in terms of the elements in BSM.

We also designed a class diagram shown in Fig. 4 to conceptually describe how the defined concepts are related to each other. From a BM, a test set can be generated, based on the test case generation strategies (Section 4.1.2). A test set is composed of a set of test cases, which can be a path or a parallel path. A path is characterized by two properties *isSimple* and *isDeep*. A parallel path is a special type of path, which should be composed of at least two paths. A deep (simple) parallel path means that all its contained paths are all deep (simple) paths. Each test case is a deep path. A test case can be an abstract or executable test case. For each path, one can obtain information that should be associated with it, such as values for *NU* and *US*.

4.1.2 Strategies

In the literature, a number of state machine based test case generation strategies have been proposed, including *All Transitions*, *All States* and *All Predicates* [37-40]. For

UncerTest, we propose two test case generation strategies. One is *All Simple Paths* (ASP) and the other is *All Paths with Maximum Path Length* (AMP). ASP is proposed because it is simple and therefore low cost. AMP is proposed because it can be configured 1) according to specific needs (e.g., saving cost by generating less number of test cases), 2) to subsume the *All Transitions*, *All States*, and *All Predicates* coverage criteria when needed, 3) to generate a larger size of test set from a BM (which are more diverse in terms of attached uncertainty information) to compare with for example *All States*, such that eventually, it forms a better pool for test minimization, 4) to subsume the *All Uncertainty* coverage, which we define as covering all states and transitions with uncertainty. In the rest of the section, we discuss ASP and AMP, respectively.

All Simple Paths Strategy (ASP)

strategy: The test set generated using this strategy is the cross product of all the possible *simple deep paths* across all the regions. For example, in Region 1, there are two simple paths: $\bar{P}_{1,1} = (S0, T1, S1, T2, S3, T3, F1)$, $\bar{P}_{1,2} = (S0, T1, S1, T2, S2, T4, S4, T5, F1)$. $\bar{P}_{1,1}$ is *deep*, but $\bar{P}_{1,2}$ is not. Further, we flatten the composite state S4, which leads to two simple paths (i.e., $(S4.0, T4.1, S4.1, T4.2, F2)$ and $(S4.0, T4.1, S4.1, T4.3, S4.2, T4.5, F3)$). We, thus, extend $\bar{P}_{1,2}$ with these two simple paths into two deep simple paths ($\bar{P}'_{1,2,1}$ and $\bar{P}'_{1,2,2}$ as shown in Fig. 3). The total number of deep paths in Region 1 is therefore three. In Region 2, there are three simple paths that are also deep. In total, the number of test cases generated with this strategy is $3 \times 3 = 9$.

All Paths with Maximum Path Length (AMP) strategy: The test set generated with this strategy consists of all possible *deep paths* with loops allowed and all the lengths of these paths should not be longer than the maximum allowed length, which is configurable (as discussed above) and should be pre-defined before applying the test generation strategy. For example, one way of defining the maximum allowed length for generating paths for a region is to calculate the total number of states and transitions contained in the region. For example, in Region 2, the maximum allowed length is 15.

After applying the test case generation strategies, each abstract test case t_i in T (Def16) has the following associated attributes: 1) the number of uncertainties in t_i ($NU(t_i)$, Def14); 2) the uncertainty measure (*UM*) of t_i ($UM(t_i)$, Def15); 3) the set of uncertainty spaces in t_i ($USP_{t_i} = \{USP_j' | 0 < j < nusp_{t_i}\}$); and 4) the set of unique transitions in t_i , $TR_{t_i} = \{tr_j' | 0 < j < ntr_{t_i}\}$.

4.2 Uncertainty-Wise Test Case Minimization

4.2.1 Problem Representation

Depending on which test case generation strategy to apply, how it is configured (for AMP) and how complex a CPS

under test is, the number of generated abstract test cases can potentially be very large and it would be practically impossible to execute executable test cases generated from all of them within a limited time budget. It is, therefore, important to minimize the number of test cases to be executed based on various attributes associated with each test case.

4.2.2 Definitions and Functions of the Six Minimization Objectives

O 1. Percentage of Test Case Minimization (PTM)

PTM measures the percentage of the selected test cases in a solution T_{sub} , which is calculated as in

$$PTM = \frac{mt}{nt} \times 100\% \quad (1)$$

where nt is the number of test cases in T ; and mt is the number of test cases in T_{sub} .

O 2. Average Normalized Number of Uncertainties Covered (ANU)

ANU measures the average normalized number of uncertainties covered by the selected test cases of a solution. For each test case t_i' , the number of uncertainties covered is $NU(t_i')$, which can then be normalized [1] as:

$$nor(NU(t_i')) = \frac{NU(t_i')}{NU(t_i') + 1} \quad (2)$$

The *ANU* for the selected test cases is calculated as:

$$ANU = \frac{\sum_{i=1}^{mt} nor(NU(t_i'))}{mt} \quad (3)$$

O 3. Percentage of Uncertainty Space Covered (PUS)

PUS measures the percentage of the total set of uncertainty spaces of a BSM covered by the selected test cases of a solution. Suppose, the set of uncertainty space of the BSM is $USP_{SM} = \{US_i | 0 < i \leq nusp\}$ and the set of uncertainty spaces of the selected test cases is the intersection of the uncertainty spaces across each test case t_i' , $USP_{sub} = \cap_{i=1}^{mt} USP_{t_i'} = \{US_i' | 0 < i \leq musp\} \subseteq USP_{SM}$.

PUS is then defined as:

$$PUS = \frac{musp}{nusp} \times 100\% \quad (4)$$

O 4. Average Overall Uncertainty Measure (AUM)

AUM is the overall uncertainty measure of the selected test cases of a solution. Note that for test case t_i' , $UM(t_i')$ is calculated using Uncertainty Theory (Section 4.1.1). The overall average uncertainty is thus calculated as:

$$AUM = \frac{\sum_{i=1}^{mt} UM(t_i')}{mt} \quad (5)$$

O 5. Percentage of Unique Uncertainties Covered (PUU)

PUU measures the percentage of the total number of unique uncertainties covered by the selected test cases of a solution. Suppose that the set of unique uncertainties in a BSM is $UU_{SM} = \{U_i | 0 < i \leq nuu\}$ and the set of unique uncertainties of the selected test cases is the intersection of the unique uncertainties across each test case t_i' , $UU_{sub} = \cap_{i=1}^{mt} UU_{t_i'} = \{U_i' | 0 < i \leq muu\} \subseteq UU_{SM}$, then *PUU* is calculated as:

$$PUU = \frac{muu}{nuu} \times 100\% \quad (6)$$

O 6. Percentage of Transition Coverage (PTR)

PTR measures the percentage of the total number of transitions in a BSM covered by the selected test cases of a solution. According to Def1, ntr is the total number of transitions in a BSM. Suppose that mtr is the number of transitions in the selected test cases (the size of the interactions among the transition sets of each selected test case t_i' , $TR_{sub} = \cap_{i=1}^{mt} TR_{t_i'} = \{tr_i' | 0 < i \leq mtr\}$). *PTR* is calculated as:

$$PTR = \frac{mtr}{ntr} \times 100\% \quad (7)$$

4.2.3 Uncertainty-wise Test Case Minimization Problems

Based on the overall problem representation and the definitions of the six objectives, we define the following four concrete test case minimization problems:

Problem 1. Search for a solution T_{sub} to achieve: 1) low *PTM*; 2) high *ANU*; and 3) high *PTR*.

Problem 2. Search for a solution T_{sub} to achieve: 1) low *PTM*; 2) high *PUS*; and 3) high *PTR*.

Problem 3. Search for a solution T_{sub} to achieve: 1) low *PTM*; 2) high *AUM*; and 3) high *PTR*.

Problem 4. Search for a solution T_{sub} to achieve: 1) low *PTM*; 2) high *PUU*; and 3) high *PTR*.

Note that these four problems share the first and last objectives, which are very typical for many test case minimization problems. However, the variation is on the second objective; each problem takes into account of uncertainty from a different perspective.

4.3 Executable Test Case Generation

In our context, generating executable test cases from abstract test cases (Section 4.1) is mainly concerned with how to enable indeterminacy sources that are specified as part of the test ready models and how to generate test data.

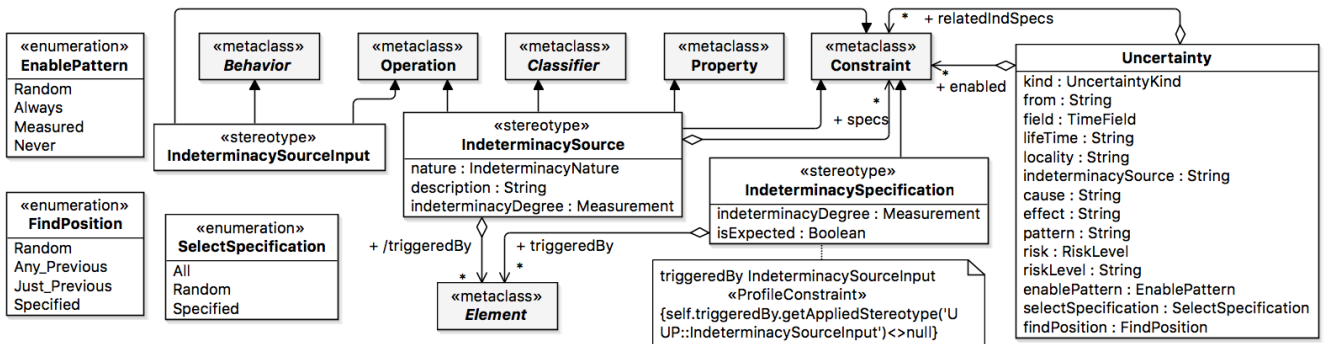


Fig. 5. Profile Diagram of IndeterminacySource (Partial)

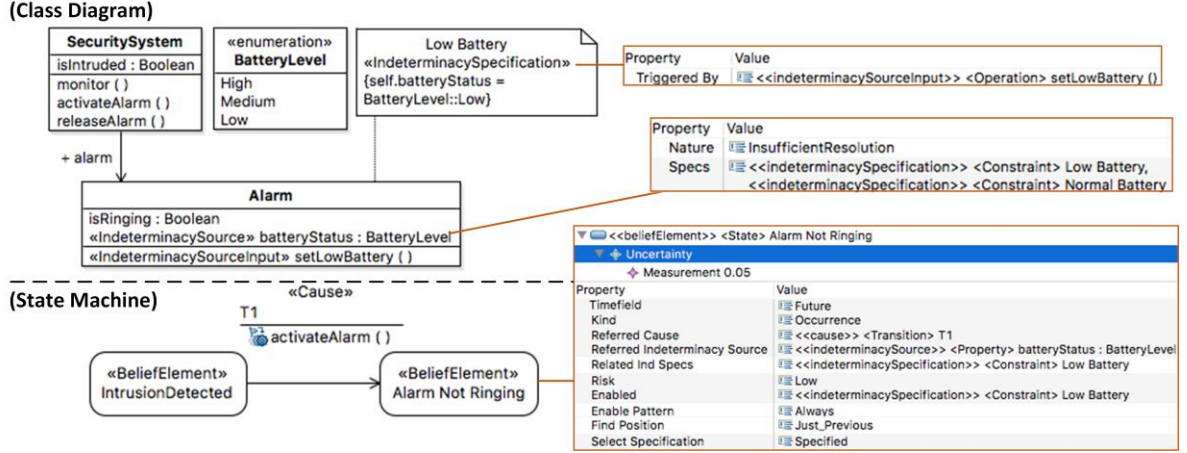


Fig. 6. An IndeterminacySource Modeling (Class Diagram and State Machine) Example for the SafeHome (Partial)

4.3.1 Enabling Indeterminacy

Since we focus on testing a CPS in the presence of environmental uncertainties, we need to introduce uncertainties in the physical environment that lead to uncertain behaviors of the CPS. To achieve this, we need to model such environmental uncertainties (named as “Indeterminacy Sources” for being more precise) in the environment that lead to observe uncertainties in the CPS.

Fig. 5 shows part of the UUP profile (Section 2.1) for modeling indeterminacy sources. As shown in Fig. 5, we provide a set of options to model indeterminacy sources, e.g., as a UML Operation and a constraint specified in Object Constraint Language (OCL) [42]. An indeterminacy source always has 1.* indeterminacy specifications, i.e., «IndeterminacySpecification» (conditions) that must be true for an indeterminacy source to occur. The «IndeterminacySourceInput» specifies the action that triggers the occurrence of «IndeterminacySource».

It is possible to model these indeterminacy related concepts in different ways. Therefore, to ease the modeling process, we summarize our recommendations for applying this part of the profile in TABLE 2, based on our experience. For example, in the first situation (as described as S1 in TABLE 2), we recommend modeling an indeterminacy source as a UML *Property*, when states of a CPS or its environment can be directly accessed and are indeterminate. For example, as shown in Fig. 6, the *batteryStatus* attribute in the *Alarm* class is an indeterminacy source. Its indeterminacy specification is modeled as an OCL constraint: “self.batteryStatus = BatteryLevel::Low”, whereas it can be triggered by the *setLowBattery()* operation (the indeterminacy source input). Fig. 6 also shows that «BeliefElement» is applied to the *Alarm Not Ringing* state and it is linked to the indeterminacy source of *batteryStatus* (via the *Referred Indeterminacy Source* attribute of «BeliefElement») to signify that it is one of the sources that lead to the uncertainty associated with the *Alarm Not Ringing* state.

Note that for the first and third situations (S1 and S3 in TABLE 2), we recommend two ways of specifying an indeterminacy source input: specifying it as an Operation without parameters (*Op1*) and specifying it as an Operation with parameter(s) constrained with a constraint specified

using OCL (*Op2*). In addition, for S1 and S3, an indeterminacy source can be specified as a property (*R1*) or constraint (*R2*). If it is *R2*, its corresponding indeterminacy specification(s) can then be simply specified as *FALSE* by default and must be switched to *TRUE* to enable the related indeterminacy source.

TABLE 2

RECOMMENDATIONS FOR APPLYING THE INDETERMINACY SOURCE PART OF THE UUP PROFILE

#	Stereotype Applied	Base Element
<i>S1: States of the environment of the CPS are indeterminate, such as the batteryStatus example shown in Fig. 6 and described in Section 4.3.1.</i>		
R1	«IndeterminacySource»	Property
	«IndeterminacySpecification»	Constraint
	Op1 «IndeterminacySourceInput»	Operation
R2	«IndeterminacySource»	Constraint
	«IndeterminacySpecification»	FALSE (default)
	Op1 «IndeterminacySourceInput»	Operation
Op2 «IndeterminacySourceInput»		Operation, Constraint
<i>S2: Input data is indeterminate.</i>		
R1	«IndeterminacySource»	Operation
	«IndeterminacySpecification»	Constraint
	«IndeterminacySourceInput»	Constraint
<i>S3: Occurrences of an event from the environment (e.g., “pressing the button”) are indeterminate.</i>		
R1	«IndeterminacySource»	Property
	«IndeterminacySpecification»	Constraint
	Op1 «IndeterminacySourceInput»	Operation
R2	«IndeterminacySource»	Constraint
	«IndeterminacySpecification»	FALSE (default)
	Op1 «IndeterminacySourceInput»	Operation
Op2 «IndeterminacySourceInput»		Operation, Constraint

In addition, we propose three mechanisms (i.e., *EnablePattern*, *SelectSpecification* and *FindPosition*), discussed below, to enable an indeterminacy source associated with a specific uncertainty, their corresponding indeterminacy specifications and inputs during test execution.

EnablePattern provides four ways of enabling an indeterminacy source: 1) *Random* – the indeterminacy source is introduced randomly (from the uniform random distribution) during execution; 2) *Always* – the indeterminacy source is always enabled during execution; 3) *Measured* – the indeterminacy source is enabled during execution by a specified measurement, e.g., with a normal distribution; and 4) *Never* – the indeterminacy source is never enabled during the execution. Choosing which option is dependent

on how much knowledge information (e.g., experience, historical data) one has about the system.

SelectSpecification provides three ways of selecting which indeterminacy specification(s) of an indeterminacy source to be enabled during test execution: 1) *All* – all associated indeterminacy specifications are enabled; 2) *Random* – enable a random number of randomly selected specification(s) from all the specifications associated with the indeterminacy source during test execution; and 3) *Specified* – the indeterminacy specification(s) specified with the “enabled” attribute is enabled during the test execution. Similarly, which option to take is highly dependent on users’ experience, knowledge and available historical data.

FindPosition is about finding a position of a path generated with the *UncerTest* abstract test case generation strategy (Section 4.1), at which an indeterminacy source should be enabled. We define four options for *FindPosition*: 1) *Random* – the position is generated randomly; 2) *Any_Previous* – the position can be any previous position before the occurrence of the associated uncertainty; 3) *Just_Previous* – the position is exactly the position right before the occurrence of the associated uncertainty; and 4) *Specified* – the exact position is modeled in the test ready model. Option 1 is recommended when we have no particular preferences or guidance. Option 2 is recommended when one wants to test, if possible, whether the uncertainty is actually due to the indeterminacy source enabled. Option 3 should be used when one wants to know whether the occurrence of the uncertainty is due to its previous step. Option 4 should be used when one has a specific position in mind, based on for example previous experience or historical data.

Note that the three mechanisms can be configured by users to form a concrete strategy (as part of an overall test strategy) for enabling an indeterminacy source associated with an uncertainty and all or part of its associated indeterminacy specifications, at a particular position of a path, which is eventually transformed into executable test cases and executed. In Fig. 6, we show an example of such configurations for enabling the indeterminacy source of *batteryStatus*, that is, the *SelectSpecification::Specified* inde-

terminacy specification (i.e., *Low Battery*) should be enabled by following the *EnablePattern::Random* pattern at the *FindPosition::Any_Previous* position during the execution.

4.3.2 Test Setup and Test Data Generation

When generating executable test cases, test configuration and concrete test data are needed. When applying *UncerTum*, test configuration is recommended to be specified as a UML object diagram organized in a package. All the objects and their relationships in this test configuration package will be instantiated before executing test cases.

First, test data generation is needed for triggering call events on transitions. In this case, a guard condition (specified as an OCL constraint) on a transition specifies the valid set of values, with which the call event can be invoked. We used an existing test data generation tool called *EsOCL* [43], which takes an OCL constraint as an input and generates a set of values that satisfy the constraint. These values are then used as test data in executable test cases.

Second, test data might be needed to trigger occurrences of indeterminacy sources. For any indeterminacy source input that is specified as a stereotyped *Constraint* or as a stereotyped *Operation* with its parameters constrained with a constraint, we rely on the *EsOCL* tool [43] to solve the constraint to generate test data. For any indeterminacy source input that is specified as an operation that has no any parameter, no data needs to be generated to trigger the operation and therefore the indeterminacy input.

4.4 Test Execution and Reporting

In addition to test verdicts for test cases, to evaluate occurrences of uncertainties during test execution, we define uncertainty-wise test verdicts as shown in Fig. 7 (the conceptual model) and TABLE 3 (definitions).

As shown in Fig. 7, an *UncerTestCaseVerdict* is modeled as a sequence of *UncerVerdicts* for specifying a set of possible evaluations of a test case, including the uncertainty aspect (e.g., known uncertainty occurred (i.e., *KnOccurred*)) and classical test case verdicts (e.g., *Pass*). An *UncerVerdict* specifies a set of possible evaluations of a test oracle in

TABLE 3
UNCERTAINTY-WISE TEST VERDICTS – DEFINITIONS OF THE LITERALS OF THE ENUMERATIONS (FIG. 7)

Literal	Definition
UncerVerdictKind: It presents the kinds of verdicts for an uncertainty.	
KnOccurred-With-InS	Known uncertainty occurred under the occurrence of a specified indeterminacy source.
KnOccurred-Without-InS	Known uncertainty occurred under the non-occurrence of any specified indeterminacy source.
KnNotOccurred-With-InS	Known uncertainty did not occur under the occurrence of any specified indeterminacy source, but at least one of alternative uncertainty occurred.
KnNotOccurred-Without-InS	Known uncertainty did not occur under the non-occurrence of any specified indeterminacy source, but at least another uncertainty within the same uncertainty space occurred.
KnOccurred-UkInS	Known uncertainty occurred but its related indeterminacy source is unknown.
KnNotOccurred-UkInS	Known uncertainty did not occur and its related indeterminacy source is unknown.
UkOccurred	Known uncertainty did not occur and none of other uncertainties in the same uncertainty space occurred.
UncerTestCaseVerdictKind: It presents the kinds of the verdicts for a test case.	
KnOccurred	At least one known uncertainty (with any of the three KnOccurred types of <i>UncerVerdictKind</i>) occurred but no UkOccurred.
UkOccurred	At least one UkOccurred.
NotOccurred	All uncertainties are evaluated to be any of the three KnNotOccurred kinds of <i>UncerVerdictKind</i> .
Pass	The execution result of the test case, for which no uncertainty is specified, adheres to the expectations [37].
Fail	The execution result of the test case, for which no uncertainty is specified, differs from the expectations [37].
Error	An error is detected.
Inconclusive	The test case execution result cannot be classified as Pass, Fail, Error, KnOccurred, UkOccurred or NotOccurred.
None	A test case has not been executed yet.

terms of a specific uncertainty. The seven kinds of uncertainty verdicts are listed as the seven literals of enumeration *UncerVerdictKind*. Their definitions are provided in TABLE 3.

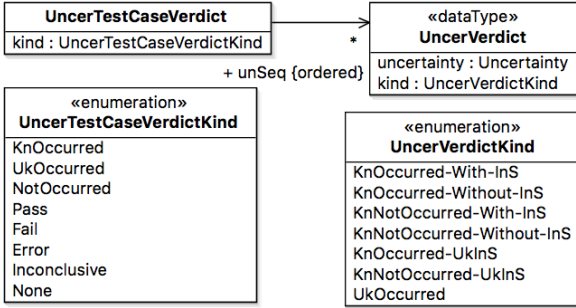


Fig. 7. Uncertainty-wise Test Verdicts – Conceptual Model

5 EVALUATION

5.1 Case Study

To assess the cost-effectiveness of UncerTest, we selected two industrial CPS case studies.

The first case study is *GeoSports* and the system monitors the performance (e.g., speed and position) and health conditions of players both individually and as a team during a game with the ultimate objective of improving their performance. The *GeoSports* application that we tested is deployed for Bandy (a type of ice hockey commonly played in the northern Europe) and uses the Quuppa system [44]. The testing infrastructure for Bandy is shown in Fig. 8. Instead of using real players to execute test cases, our industrial partner, Nordic Med Test [45] has deployed a set of test rigs for replacing players. Each test rig has one Quuppa device attached to it. The device communicates its position with one or more locators (antennas) via Bluetooth connections and the locators receive those positions and send them to the Quuppa Server (QPE). The access to the devices, locators, and the QPE server are available as REST APIs. In addition, a set of test APIs were implemented by the partner as REST APIs for controlling the test rigs. Notice that we only tested the positioning system in this paper, i.e., collecting the positions from Quuppa tags and transmitting them to the QPE server via locators.

The second case study is Automated Warehouse (AW) provided by ULMA Handling Systems [25], Spain. ULMA develops automated handling systems

for worldwide warehouses of different natures such as Food and Beverages, Industrial, Textile, and Storage. Each handling facility (e.g., cranes, conveyors, sorting systems, picking systems, rolling tables, lifts, and intermediate storage) forms a physical unit and together they are deployed to one handling system application (e.g., Storage). A handling system cloud supervision system (HSCS) generally interacts with diverse types of physical units, network equipment, and cloud services. Application-specific processes in HSCS are executed spanning clouds and CPS requiring different configurations. This case study implements several key industrial scenarios, i.e. introducing a large number of pallets to the warehouse, transferring the items by Stacker Crane. To test these scenarios, ULMA [25] and IK4-Ikerlan [46] developed and provided relevant simulators and emulators as shown in Fig. 8. Further details on the case studies can be consulted in [47].

The descriptive statistics for test ready models of GS and AW are reported in TABLE 4. We selected one use case for GS case study and four use cases for the AW case study. For each use case, we selected the number of elements stereotyped as «BeliefElement» (#Belief), uncertainties (#U), known indeterminacy sources (#IndS), known indeterminacy source specifications (#IndSpec), states (#State), and transitions (#Tran).

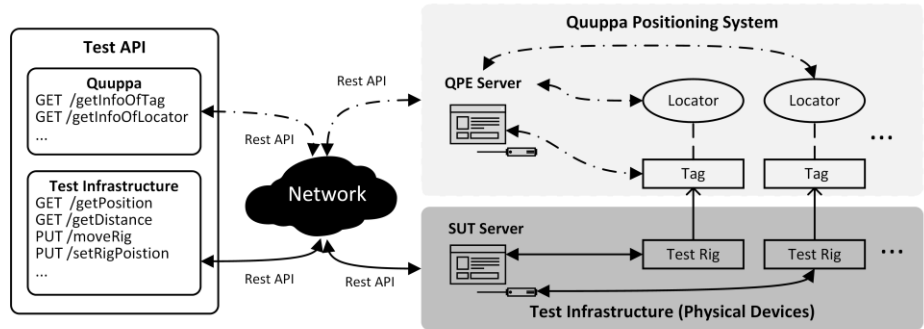
TABLE 4

DESCRIPTIVE STATISTICS OF THE CASE STUDIES

Case	UC	#Belief	#U	#IndS	#IndSpec	#State	#Tran
AW	AW1	7	11	2	4	12	15
	AW2	5	9	2	4	12	18
	AW3	6	10	-	-	10	14
	AW4	7	8	1	2	16	16
GS	GS1	6	6	1	2	17	21

- means unknown indeterminacy source

(The Deployment of the GS Case Study)



(The Deployment of the AW Case Study)

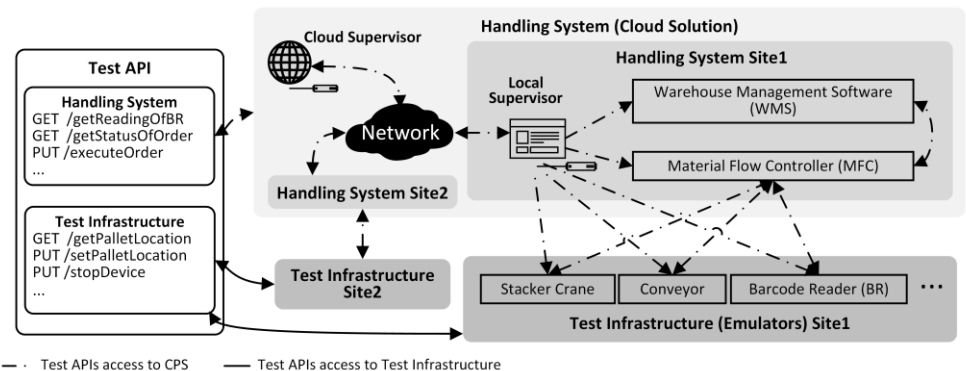


Fig. 8. The Test Execution Solution of the GS and AW Case Studies

TABLE 5
RESULTS FOR THE TEST CASE GENERATION STRATEGIES

Case	UC	Strategy	#TC (nt)	%Transition	%UU
AW	AW1	ASP	20	91.3%	100%
		AMP	420	100%	100%
	AW2	ASP	8	88.8%	100%
		AMP	776	100%	100%
	AW3	ASP	5	85.7%	80%
		AMP	857	100%	100%
	AW4	ASP	5	93.7%	100%
		AMP	296	100%	100%
GS	GS1	ASP	5	71.4%	83.3%
		AMP	1799	100%	100%

5.2 Research Questions

Our overall objective is to assess which test strategy (two test case generation strategies (results in TABLE 5) and four minimization strategies) is *cost-effective*. In total, we have five test strategies described as follows: First, test cases are generated from a BSM using *All Simple Paths* (ASP). For this strategy, the numbers of generated test cases for the two case studies are small, which thus doesn't require test case minimization. The rest of the four strategies are based on test cases generated from a BSM using AMP, followed by test case minimization based on the uncertainty related strategies defined in Section 4.2.3: average normalized number of uncertainties covered (Problem 1), percentage of uncertainty space covered (Problem 2), average overall uncertainty measure (Problem 3), and percentage of unique uncertainties covered (Problem 4). For simplicity, we refer to these strategies as S1 (ASP), S2 (AMP + Problem 1), S3 (AMP + Problem 2), S4 (AMP + Problem 3) and S5 (AMP + Problem 4) respectively in the rest of the paper. We selected eight commonly used multi-objective search algorithms from the Evolutionary Algorithm, Hybrid Algorithm, and Swarm Algorithm classifications of algorithms. Moreover, we used random search (RS) as the assessment baseline to determine whether the complex multi-objective search algorithms are needed or simply RS suffices.

Based on our overall objective, we would like to answer the following research questions.

RQ1: How does the selected multi-objective search algorithms (e.g., NSGA-II) compare to RS in terms of solving uncertainty-wise minimization problems (S2–S5)?

RQ2: Which algorithm is the best among selected ones

to solve uncertainty-wise minimization problems (S2–S5) respectively?

RQ3: Which uncertainty-wise strategy (S1-S5) is effective to discover uncertainties in the real CPS?

5.3 Design of the Evaluation

The design of our evaluation is shown in TABLE 6. In the table, we present, for each research question, which task we perform, which strategies are compared, which metrics (*Metrics* column) are used, which statistical methods (*Comparison Method* column) are applied, which algorithms are applied, and which case studies are used. Notice that, to decrease the possibility of obtaining results by chance we ran all the algorithms 100 times for each case study and each strategy [48]. We used the implementation of the eight selected multi-objective search algorithms provided by jMetal [49] and used the following default parameter settings: the *Population Size* of 100, the binary tournament for selecting parents, and the simulated binary criterion for recombination. A crossover rate of 90% was used and mutation rate was polynomial with the rate of $1.0/n$, where n is the number of the bit representation of a solution.

For RQ1 and RQ2, we compared each pair of the algorithms using HyperVolume (HV) [50] and the individual objectives that are relevant for each strategy. For example, O2 is only valid for S2. HV was selected based on the guidelines for choosing a quality indicator for search-based software engineering problems that require multi-objective optimization [51]. Based on the guidelines for reporting results for search-based software engineering problems [52], we chose Vargha and Delaney statistics (\hat{A}_{12}) and the Mann Whitney U Test (p -value) to compare the eight selected multi-objective search algorithms with RS for S2–S5.

Results of test case generation for each case study with each test strategy are represented in TABLE 5. For S1, the numbers of test cases generated with ASP for all the case studies were small and didn't require minimization. For S2–S5, we ran each problem 100 times and thus we combined all the solutions from all the runs for comparison to answer RQ1 and RQ2. To compare the performance of the algorithms, we designed a mechanism to rank all the algorithms based on the \hat{A}_{12} values and p -values for each metric as shown in the rank algorithm (Fig. 9). Furthermore, we calculate the confidence for nine algorithms as shown

TABLE 6
DESIGN OF THE EVALUATION

RQ	Experiment Task	Strategy	Metric	Comparison Method	Algorithm		Case Study
1	Compare each algorithm with RS	S2 – S5	HV, PTM, ANU (only for S2), PUS (only for S3), AUM (only for S4), PUU (only for S5), PTR	Vargha and Delaney statistics (\hat{A}_{12}), Kruskal-Wallis Test, Mann-Whitney U Test (p -value)	Evolutionary Algorithm	NSGA-II [1]	AW, GS
2	Compare each pair of the multi-objective algorithms					NSGA-III [3]	
						MOCell [4, 5]	
					Hybrid Algorithm	SPEA2 [6]	
						CellIDE [9]	
						AbYSS [10]	
Swarm Algorithm	GDE3 [13]						
	SMPSO [16]						
Random Search (only for RQ1)							
3	Compare each pair of the strategies	S1 – S5	$UUDP$, NUO , Uk , $UkDDP$, EOT	Simple Comparison	The best algorithm		

in TABLE 7.

For RQ3, we picked the best algorithms (BA) for S2–S5 based on the results of RQ1 and RQ2, which were used to minimize test cases. The generated test cases for S1 and minimized test cases for S2–S5 were executed on the current deployments of the GS and AW case studies as shown in Fig. 8. The execution results for S1–S5 were evaluated based on various cost, effectiveness, and efficiency measures as shown in TABLE 7.

```

Rank Algorithm
input  algos[], len(algos)>=2
output algos[], rank[]//rank[i] is the rank value
      of algos[i]
1  n ← len(algos)
2  for i ← 1 to n
3      for j ← i+1 to n //sort algos[]
4          if better1(algos[i], algos[j])
5              switch(algos, i, j)
6  rank[1]=1;
7  for i ← 2 to n //set rank values for algos[]
8      if better1(algos[i-1], algos[i])
9          rank[i]=rank[i-1]+1;
10     else
11         rank[i]=rank[i-1];

```

¹ Function *better*(*algo1*, *algo2*) compares *algo1* with *algo2*. It returns the best algorithm based on the following two conditions: 1) for HV, p-value<0.05 and A12>0.5; 2) p-value<0.05 and A12<0.5

Fig. 9 Algorithm for Ranking

5.4 Results and Analyses

In this section, we present results and analyses for the three research questions.

5.4.1 Results for RQ1

Recall that RQ1 focuses on comparing the eight selected multi-objective search algorithms with RS based on the individual objectives, HV for (S2–S5) minimization problems. Due to the large number of comparisons, the detailed results in terms of rank values, p-values and \widehat{A}_{12} values are

provided in Appendix A. The summarized results in terms of confidence and risk based on the rank of each algorithm are presented in TABLE 9 for each case study. For S2–S5, for each use case, we can see that RS has the lowest confidence to be the best algorithm (the *Conf.* column). These results suggest that our problems couldn't have been solved effectively with RS and thus the use of complex multi-objective search algorithms is justified.

5.4.2 Results for RQ2

For RQ2, the detailed results of comparison of each pair of algorithms (C_2^9 , i.e., 36 pair-wise comparisons) for each case study for the S2–S5 strategies, in terms of rank values, p-values and \widehat{A}_{12} values are provided in Appendix A. The summarized results in terms of confidence of each algorithm, for each use case are presented in TABLE 9.

As we can see in TABLE 9, in terms of confidence for S2–S5, SPEA2 is consistently the best, or the second best (only for three instances). Based on the results, we recommend using SPEA2 with S2–S5 to find the most optimal minimized test cases.

5.4.3 Results for RQ3

To answer RQ3, we chose SPEA2 to minimize test cases for S2–S5 for both of the case studies and minimized test cases were executed. The test execution results of S1–S5 are provided in TABLE 8 and we compare S1–S5 based on various cost, effectiveness, and efficiency measures (TABLE 7). In terms of execution time (i.e., a cost measure) presented in the column ET (s) in TABLE 7, we can observe that S2 took the highest time to execute the minimized test cases for all the use cases except for AW1, where S4 took the highest time to execute test cases.

In TABLE 8, the *nt* column shows the number of test cases for each test strategy (S1–S5). Recall from TABLE 7 that the *UUDP* column shows the percentage of times that the introduced indeterminacy sources led to observing corresponding uncertainties during test execution, whereas

TABLE 7
DEFINITIONS OF METRICS FOR EACH RESEARCH QUESTION

RQ	Metric	Definitions
RQ1		$A = \{NSAG-II, NSGA-III, MOCell, SPEA2, CellDE, AbYSS, GDE3, SMPSO, RS\}$, $S = \{S2, S3, S4, S5\}$, $S2 = \{PTM, ANU, PTR, HV\}$, $S3 = \{PTM, PUS, PTR, HV\}$, $S4 = \{PTM, AUM, PTR, HV\}$, $S5 = \{PTM, PUU, PTR, HV\}$. Note that 1) A_k represents the j th A , e.g. $A_1 = NSGA-II$; 2) S_{ij} represents the j th objective of the i th strategy, e.g., $S_1 = S2$, $S_{11} = PTM$.
RQ2	Rank of Algorithm for the objectives of the strategies	$Rank_{A_k}^{S_{ij}}$ is the rank value of the A_k algorithm, for the j th objective of S_i strategy, which is calculated as $rank[k]$ in Fig. 9.
	Confidence of Algorithm for the objectives of the strategies	Confidence of each objective of each strategy is to calculate the percentage of being better than the other algorithms, which is calculated as $Confidence_{A_k}^{S_{ij}} = (Rank_{A_k}^{S_{ij}} / \sum_{n=1}^9 Rank_{A_n}^{S_{ij}}) \times 100\%$.
	Confidence of Algorithm for the strategies	Confidence of each strategy is to calculate the average confidence of each objective, which is calculated as $Confidence_{A_k}^{S_i} = (\sum_{n=1}^4 Confidence_{A_k}^{S_{in}} / 4) \times 100\%$.
RQ3	Effectiveness	<div> <div><i>UUDP</i></div> <div>Unique uncertainty detection percentage is calculated as $UUDP = NUUO/NUU$, where $NUUO$ is the number of unique uncertainties occurred during the test set execution.</div> </div> <div> <div><i>NUO</i></div> <div>The number of uncertainties occurred during the test set execution, which includes the occurrence of the uncertainties with the occurrence of their specified indeterminacy sources (NUO_{Ind}) or unknown indeterminacy sources (NUO_{UnkInd}).</div> </div> <div> <div><i>Error</i></div> <div>The number of errors found during the test execution.</div> </div> <div> <div><i>Uk</i></div> <div>The number of unknown uncertainties occurred during the test set execution.</div> </div> <div> <div><i>UkDP</i></div> <div>Unknown uncertainty detection percentage is calculated as $UkDP = Uk/NUU$.</div> </div>
	Cost	<i>ET</i> ET is the execution time of the test set.
	Efficiency	<i>EOT</i> The efficiency in terms of time includes 1) $EoT(NUO)$ is the efficiency of uncertainty detection calculated as $EOT(NUO) = NUO/ET$; 2) $EoT(Uk)$ is the efficiency of unknown uncertainty detection calculated as $EOT(Uk) = (Uk)/ET$.

TABLE 9
CONFIDENCE FOR EACH ALGORITHM FOR EACH STRATEGY
AND EACH CASE STUDY

Str.	Algo.	AW1	AW2	AW3	AW4	GS1
S2	NSGA2	13%	12%	13%	9%	12%
	NSGA3	14%	14%	12%	12%	15%
	MoCell	8%	8%	8%	9%	9%
	SPEA2	15%	17%	16%	15%	15%
	AbYSS	9%	13%	12%	10%	14%
	CellIDE	8%	5%	7%	8%	7%
	GDE3	14%	10%	10%	15%	10%
	SMPSO	14%	15%	17%	14%	12%
S3	RS	5%	5%	5%	7%	6%
	NSGA2	13%	13%	13%	12%	11%
	NSGA3	13%	13%	13%	12%	13%
	MoCell	8%	9%	9%	9%	9%
	SPEA2	14%	15%	15%	13%	15%
	AbYSS	10%	12%	12%	11%	14%
	CellIDE	8%	7%	7%	10%	7%
	GDE3	12%	10%	10%	13%	10%
S4	SMPSO	14%	13%	13%	12%	14%
	RS	8%	7%	7%	9%	7%
	NSGA2	13%	15%	14%	11%	14%
	NSGA3	13%	13%	13%	13%	13%
	MoCell	9%	7%	7%	8%	8%
	SPEA2	16%	17%	17%	16%	16%
	AbYSS	10%	10%	12%	10%	13%
	CellIDE	6%	5%	5%	7%	5%
S5	GDE3	13%	10%	10%	15%	10%
	SMPSO	15%	16%	18%	14%	15%
	RS	6%	5%	5%	7%	5%
	NSGA2	13%	13%	13%	11%	12%
	NSGA3	13%	13%	13%	11%	12%
	MoCell	8%	9%	9%	9%	9%
	SPEA2	13%	15%	15%	13%	15%
	AbYSS	10%	12%	12%	12%	13%
S6	CellIDE	8%	7%	7%	10%	7%
	GDE3	12%	10%	10%	13%	10%
	SMPSO	13%	13%	13%	12%	14%
	RS	8%	7%	7%	9%	7%

the *NUO* column represents the number of uncertainties that were observed as the result of test execution. As one can see from TABLE 8, consistently for all the five use cases, test cases with the S2 strategy always led to observe more uncertainties as compared to the rest of the strategies (the *NUO* column). The *NUO_{Ind}* (defined in TABLE 7) column shows the number of uncertainties out of *NUO* that occurred because of known indeterminacy sources, whereas the *NUO_{ukInd}* column (definition in TABLE 7) shows the number of uncertainties observed due to unknown indeterminacy sources. Once again S2 is the best across the case studies in terms of *NUO_{Ind}*. In terms of *NUO_{ukInd}* (except for AW1 where S4 is the best), S2 is the best across the case studies. Even for AW1, S4 observed only one more uncertainty than S2.

The *Uk* (defined in TABLE 7) column represents the number of unknown uncertainties observed due to unknown indeterminacy sources. For AW1, with S4, 16 uncertainties in this category were observed, whereas the second highest was 13 with S2. The *Error* column represents the number of error detected with each test strategy. For AW1 and AW2, both S2 and S4 observed one error each, whereas, for AW3, S2 observed four errors, i.e., higher than the other strategies.

Based on the above results, we recommend using S2 since it performed better than the rest of the strategies in terms of the studied effectiveness measures except for *Uk* and *NUO_{ukInd}* for AW1, where S4 was the second best.

We also compare the strategies based on the defined efficiency measures and the results are presented in the last two columns of TABLE 7. Note that efficiency measures simply tell that how many uncertainties (measured with the two uncertainty related measures, i.e., *Uk* and *NUO*) were observed per minute. For AW1, AW2, and AW3, for the *EoT(NUO)/min* measure, S5 is the best. For AW4, S3 is

TABLE 8
RESULTS FOR RQ3

UC	Str.	nt	PTR	ET (s)	UUDP	NUO	NUO _{Ind}	NUO _{ukInd}	Uk	Error	UkDP	EoT(NUO)/min	EoT(Uk)/min
AW1	S1	20	91.3%	216	45%	25	16	9	10	0	91%	0.116	2.78
	S2	22	100%	291	45%	36	23	13	13	1	118%	0.124	2.68
	S3	17	100%	244	45%	30	18	12	11	0	100%	0.123	2.70
	S4	20	96%	519	36%	29	15	14	16	1	145%	0.056	1.85
	S5	14	100%	170	45%	22	13	9	11	0	100%	0.130	3.88
AW2	S1	8	88.8%	387	67%	11	8	3	0	0	0%	0.028	0
	S2	106	100%	2134	78%	314	205	109	0	4	0%	0.147	0
	S3	20	100%	866	78%	52	35	17	0	2	0%	0.060	0
	S4	54	100%	1114	78%	148	97	51	0	3	0%	0.133	0
	S5	30	100%	501	78%	91	58	33	0	2	0%	0.182	0
AW3	S1	5	85.7%	3156	60%	8	-	-	0	0	0%	0.003	0
	S2	138	100%	99414	100%	955	-	-	0	1	0%	0.010	0
	S3	45	100%	29147	100%	271	-	-	0	0	0%	0.009	0
	S4	92	100%	54990	100%	568	-	-	0	1	0%	0.010	0
	S5	47	100%	30663	100%	305	-	-	0	0	0%	0.010	0
AW4	S1	4	93.7%	8	75%	9	5	4	0	0	0%	1.089	0
	S2	24	100%	155	75%	296	163	133	0	0	0%	1.909	0
	S3	2	81%	11	63%	23	11	12	0	0	0%	2.116	0
	S4	7	94%	38	75%	79	38	41	0	0	0%	2.105	0
	S5	4	94%	20	75%	38	20	18	0	0	0%	1.913	0
GS1	S1	5	71.4%	88	33%	2	1	1	0	0	0%	0.023	0
	S2	393	95%	29300	83%	1767	569	1198	0	0	0%	0.060	0
	S3	177	100%	12107	83%	717	211	506	0	0	0%	0.059	0
	S4	203	100%	12717	67%	835	259	576	0	0	0%	0.066	0
	S5	174	100%	11428	83%	715	243	472	0	0	0%	0.063	0

the best with an efficiency value of 2.116 for $EoT(NUO)/min$, whereas, for GS, S4 is the best with an efficiency value of 0.066 for $EoT(NUO)/min$. However, the differences of these two with the efficiency values of S5 are not much. For example, for GS, S5 has as efficiency value of 0.063, i.e., the difference of 0.003 with S4. This means that S5 is likely to observe 0.003 fewer uncertainties than S4 per minutes. Such difference is negligible in practice. In terms of $EoT(Uk)/min$ for AW1, once again S5 is the best strategy.

Based on the above results, we suggest using S2 when the test execution time is not a concern; otherwise, we recommend using S5 since it is highly likely to be efficient.

5.5 Discussion

Based on the results and analysis of RQ1, we can conclude that our uncertainty-wise test minimization approaches are complex and thus RS was not sufficient to solve our problems. RS has the lowest confidence to be the best algorithm (i.e., 5.28% on average) as compared to the rest of the algorithms when studying the results of all the use cases together.

In terms of comparing the selected multi-objective search algorithms for the four uncertainty-wise test minimization problems (RQ2), we found that SPEA2 has the highest confidence to be the best algorithm (i.e., 12.12% on average) as compared to the rest of the algorithms including RS.

When comparing across the five test strategies, we found S2 (i.e., AMP with minimization focused on covering the number of uncertainties) with SPEA2 turned out to be the best. S2 with SPEA2 observed on average 51%¹ more uncertainties than the rest of the strategies due to unknown indeterminacy sources when combining the results from all the use cases. Moreover, it managed to observe 13 unknown uncertainties due to unknown indeterminacy sources across all the use cases. In comparison, S4 with SPEA2 managed to observe 16 unknown uncertainties due to unknown indeterminacy sources, i.e., three more than the S2 and SPEA2 combination.

In terms of practical implications of the work, we have four key findings. First, the results of observed known uncertainties due to known indeterminacy sources (the NUO_{ind} column) simply confirm our belief about known uncertainties of a CPS. Second, the results of observed known uncertainties due to unknown indeterminacy sources (the NUO_{ukind} column) tell us that the known uncertainties can happen due to the indeterminacy sources that we weren't aware of. As a result, such unknown indeterminacy sources need to be investigated and discovered with the help of our industrial partners. Once discovered, our test ready models must be updated to reflect these indeterminacy sources. Third, the discovery of unknown uncertainties due to unknown indeterminacy sources (the Uk column) need to be investigated once again together with

our industrial partners and reflected in our test ready models as known uncertainties due to known indeterminacy sources (if investigated and found) for future testing. Fourth, the *Error* column tells the errors found during the test execution and must be fixed in the implementation of the CPSs. Note that we observed 15 times of occurrences of errors for the AW case study. Due to confidentiality issues, further details on the errors and uncertainties cannot be provided. Nonetheless, the results tell us that our proposed test strategies can help us confirming our belief about known uncertainties, discovering unknown uncertainties and unknown indeterminacy sources, and find errors.

5.6 Threats to Validity

External validity. A typical *external validity threat* with any empirical study is related to the generalization of results. Our experiment results are valid for two case studies (five use cases) from two CPS domains (Automation, Healthcare) and thus additional experiments with different case studies are required to further generalize the results.

Internal validity. There are four main internal validity threats in our experiment. First, in terms of test case generation with AMP, we used the same criteria to generate test cases for all the use cases. This includes generating test cases that must achieve the 100% transition coverage and 100% unique uncertainty coverage. Second as suggested in [52], all the SBSE problems face a common *internal validity threat* that is related to parameter settings used for the search algorithms. We used the default parameter settings for all the algorithms based on the existing guidelines [52, 53]. Third, we used the same criteria to introduce indeterminacy sources during the test execution for each use case. This means that we used the same values for *EnablePattern*, *FindPosition*, and *SelectSpecification* (Fig. 5) when executing test cases generated from each test strategy across the use cases. Fourth, the fact that executing each test case more than once can lead to different execution results. Therefore, we executed a test case exactly once if it was included in the test case sets generated by multiple test strategies.

Conclusion validity. There are two main conclusion validity threats in our experiment. First, as discussed in [54], due to randomness in search algorithms, results may have been produced by chance. We handled this threat as suggested in [54], that is to repeat the experiments 100 times. Based on the standard guidelines [52] to report search-based software engineering experiments, we chose the Kruskal-Wallis test to calculate *p*-value for multiple comparisons with 5% significance level, the Mann-Whitney U test to calculate *p*-value for pair comparison with 5% significance level, to determine practical and statistical significances of results. Second, our experiment results are based on one-time test execution due to limited resources available to execute test cases on the physical test infrastructures. Additional experiments are required in the future to execute test cases more than once to study whether executing one test case multiple times lead to observing different uncertainties.

Construct validity. As suggested in [48, 55], the same

¹ This value is calculated as $\frac{\sum_{i=1}^4 \sum_{j=1,3,4,5} (NUO_{ukind}^{UC_i S_2} - NUO_{ukind}^{UC_i S_1}) / (NUO_{ukind}^{UC_i S_2} + NUO_{ukind}^{UC_i S_1})}{4 \times 4}$, where $UC = \{AW1, AW2, AW4, GS1\}$, $S = \{S1, S2, S3, S4, S5\}$. $NUO_{ukind}^{UC_i S_1}$ is the number of uncertainties observed with S1 for the AW1 use case.

stopping criterion must be used for all the evaluated algorithms to avoid any potential bias in results. Following the guidelines, we used the same number of fitness evaluations (25000) and thus dealt with this type of validity threat.

6 AUTOMATION

The tool support for UncerTest is shown in Fig. 10, a user creates a BM, i.e., belief model (including BCDs and BSMs) in the IBM Rational Software Architect (RSA) using UncerTum implemented in the IBM RSA [19]. In addition to BCDs and BSMs, the BM also includes one or more object diagrams (corresponding to BCDs) that represent the test configuration of the CPS being tested.

The first toolset of UncerTest is referred to as *Abstract Test Case Generator*. AG1 takes BSMs as input and convert them into graphs (SMGraph) in JGraph [21] based on a test case generation strategy (Section 4.1), which can be selected by a tester. AG2 takes the graph representation of BSMs as input and converts them into deep paths using the JGraph tool [21]. Notice that multiple regions are not handled by JGraph and thus we extended it for this purpose. AG3 takes the generated deep paths as input and calculates *UM* of each path using the *Uncertainty Measurement Calculator* and produces abstract test cases and associated *UM* with each test case.

The second toolset is *Uncertainty-Wise Test Case Minimization*. The *Solution Solver* uses jMetal's implementation of the multi-objective search algorithms and RS to minimize the number of abstract test cases based on the four test case minimization strategies (Section 4.2). A tester can select any algorithm and any of the four strategies to perform test case minimization. The output is a minimized set of test cases and values for the relevant objectives (Section 4.2). The *Solution Processor* converts the output into an EMF model [56] representation, which is the key input for the third toolset.

The third toolset is *Executable Test Case Generator*. EG1 takes BCDs as input and converts them into *Java Entities*, which are further extended by a tester as *Entities Adapter* to provide actual implementation of operations, for example, how to invoke REST APIs in GS. For each case study, a user has to manually implement *Entities Adapters* to bridge the gap between model elements and implementation of Test API. EG2 takes the object diagram as input and outputs *Test Setup*, which is required for execution of test cases. Finally, EG3 takes the EMF model file as the input and invokes EsOCL [43] to obtain concrete test data. EsOCL is a search-based OCL solver that takes input an OCL constraint and provides a set of data that satisfies the constraint. Using the output from EsOCL, EG3 produces executable test cases, where each executable test case imports Eclipse OCL [57] to check OCL constraints (state invariants) at runtime, which serve as test oracles.

7 RELATED WORK

Walkinshaw and Fraser [14] proposed a black-box testing framework to select test cases for execution for the purpose of decreasing uncertainty about the correctness of a software system. The proposed framework relies on Genetic Programming (GP) [58] to infer models of a system under test. It generates random inputs and assesses them on the inferred models to select ones that create most uncertainty, and eventually only execute the selected ones on the real system under test. Uncertainty was measured in their context as the level of confidence in the corresponding output of an input (i.e., test data). UncerTest shares a similar objective, that is, selecting test cases for execution by taking into account uncertainty. Differences between the two approaches can be summarized from the three aspects: 1) UncerTest focuses on testing CPS under uncertainty, but their proposed framework is for software; 2) UncerTest requires

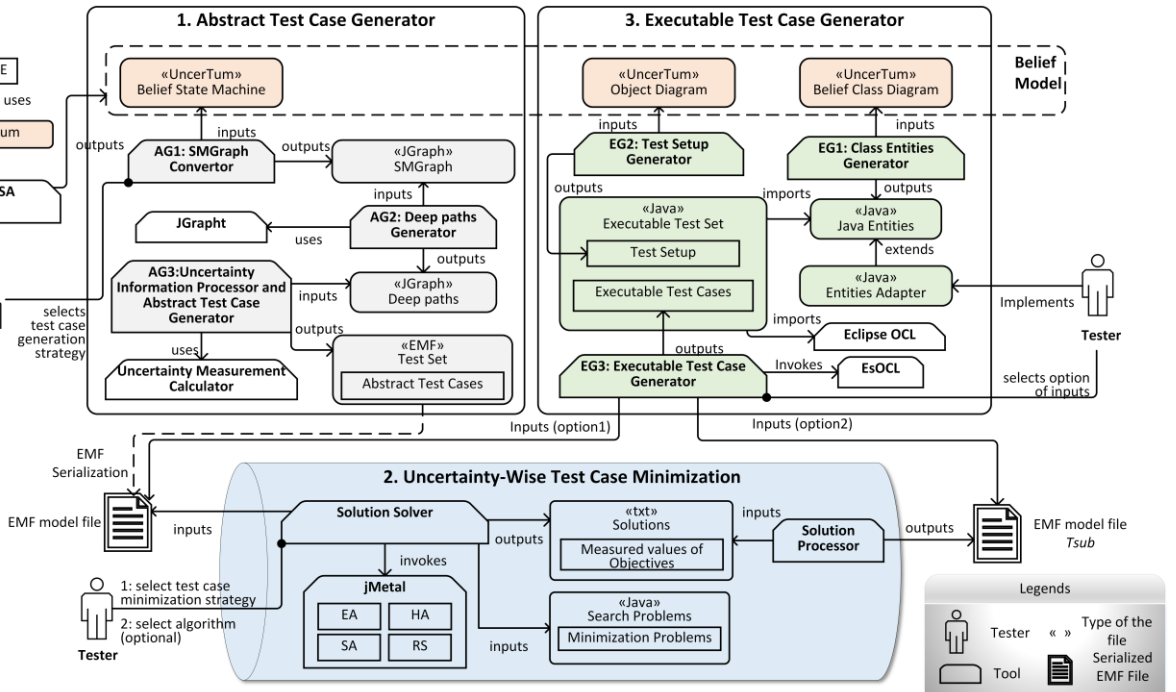


Fig. 10. Overall Automation Solution of UncerTest

initial BMs with subjective uncertainty specified as the input, whereas in their approach models are inferred by GP, which requires the execution of the software under test; and 3) UncerTest elaborates uncertainty from the four aspects (i.e., number of uncertainties, number of unique uncertainties, uncertainty space, and uncertainty measure from the Uncertainty Theory), whereas their approach is based on an existing uncertainty sampling technique.

Another related work [15] focuses exclusively on time-related uncertainty. It relies on UML sequence diagrams together with the UML Profile for Schedulability, Performance, and Time (SPT) [59]. This work, however, only supports modeling uncertainty in time on messages of sequence diagrams. As discussed in Section 2.1, UncerTest is built on UncerTum [19], which is a comprehensive modeling framework for specifying various types of uncertainty (e.g., time, content and environment). The work presented in [15] focuses on stress testing of systems in the existence of time-related uncertainty on messages, which may complement the UncerTest framework, which can be investigated in the future.

David et al. [60] presented a number of test generation principles and algorithms (e.g., the online testing tool UP-PAAL-TRON [61]) and discussed the feasibility of applying them for testing timed systems under uncertainty, at a high level of abstraction. In their context, uncertainty is mainly caused by the inherent concurrent and indeterminate nature of timed systems. UncerTest, however, addresses uncertainty with a much broader scope and has an end-to-end MBT solution.

In [62], the authors presented a solution to transform UML use case diagrams and state diagrams into usage graphs appended with probability information about expected use of the software. Such probability information can be obtained in several ways by relying on, e.g., domain expertise or usage profiles of software. Usage graphs with probability can be eventually used for testing. This work only deals with modeling uncertainty using probabilities and does not support other types of uncertainty measures such as ambiguity as supported in UncerTum. In terms of testing, the authors proposed to use an existing work [63] to generate test cases. In the context of UncerTest, we focus on test generation based on the uncertainty theory [22].

To model uncertainty (inherent in real world applications) with UML class diagrams, an extension was proposed in [64-66], which is referred to as fuzzy UML data modeling. The extension relies on two theories: fuzzy set and possibility distribution, and was later on further extended in [67] to transform fuzzy UML data models into representations in the fuzzy description logic (FDLR) to check the correctness of fuzzy properties. Furthermore, another automated transformation was proposed in [68] to transform fuzzy UML data models into web ontologies to support automated reasoning on fuzzy properties in the context of web services. These works focus on the analyses at the design time, whereas our work focuses on testing. In terms of modeling, our UncerTum focuses on uncertainty in a comprehensive and precise manner by considering various types of measures such as probability, vagueness, and fuzziness. The methodologies proposed in [64-66] for

specifying fuzzy UML data can easily integrate with our model libraries when needed and potentially used to support MBT of CPSs under uncertainty. However, this requires further investigation.

In [69], a language-independent solution was proposed partiality, *Abs* partiality, *Var* partiality and *OW* partiality, to denote the degree of incompleteness specified by model designers. The work also provides a solution for merging and reasoning possible partial models with tool support [70, 71]. The approach was demonstrated on UML class and sequence diagrams [69]. This work is related to our work in terms of expressing the uncertainty of modelers. However, in the context their work, the focus is on uncertainty in partial models for supporting model refinement and evolution. In contrast, we focus on modeling uncertainty (lack of confidence) in test ready models that are in turn used for test case generation and minimization relying on the uncertainty theory.

8 CONCLUSION

Nowadays, Cyber-Physical Systems (CPSs) are everywhere in our daily life. It is forecasted that applications of CPSs will span over many different domains in the near future, including autonomous vehicles, robotics, healthcare, industrial automation, among others. One critical dimension of the complexity of developing and testing such systems is due to the inherent uncertainty of their operational environment and uncertain behaviors of themselves. To tackle this challenge, in this paper, we proposed a model-based and search-based test case generation and minimization framework (named as UncerTest) for testing CPSs under uncertainty. UncerTest takes advantages of the uncertainty theory and search-based optimization techniques, based on which, it also proposes an innovative set of uncertainty-related test case minimization strategies. We evaluated UncerTest with two real industrial CPSs case studies and eight commonly used multi-objective search algorithms. Our best test strategy managed to discover on average 51% more uncertainties due to unknown indeterminacy sources as compared to the rest of the test strategies across the case studies. The same test strategy managed to discover 118% more unknown uncertainties as compared to the already known ones.

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Appendix A Results for Comparison among Algorithms (RQ1 and RQ2)

A.1 AW1

A.1.1 Kruskal–Wallis Test

TABLE A-1 Kruskal–Wallis Test for each objective of each strategy (AW1)

Str.	PTM		O2 of Si		PTR		HV	
	DF	Prob> ChiSq	DF	Prob> ChiSq	DF	Prob> ChiSq	DF	Prob> ChiSq
S2	8	<.0001	8	<.0001	8	<.0001	8	<.0001
S3	8	<.0001	8	<.0001	8	<.0001	8	<.0001
S4	8	<.0001	8	<.0001	8	<.0001	8	<.0001
S5	8	<.0001	8	<.0001	8	<.0001	8	<.0001

A.1.2 Mann-Whitney U Test and Vargha and Delaney statistics

TABLE A-2 Mann-Whitney U Test and Vargha and Delaney statistics for each objective of each strategy (AW1)

Str	Algorithm A	Algorithm B	PTM		O2 of Si		PTR		HV	
			\bar{A}_{12}	p-value	\bar{A}_{12}	p-value	\bar{A}_{12}	p-value	\bar{A}_{12}	p-value
S2	NSGA-II	NSGA-III	0.63	<0.05	0.41	0.09	0.5	1	0.42	0.06
		MoCell	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		SPEA2	0.96	<0.001	0.32	<0.001	0.48	0.09	<0.01	<0.001
		AbYSS	<0.01	<0.001	<0.01	<0.001	0.5	1	0.98	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	0.84	<0.001	0.29	<0.001	0.5	1	0.08	<0.001
		SMPSO	>0.99	<0.001	0.12	<0.001	0.3	<0.001	<0.01	<0.001
	RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001	
	NSGA-III	MoCell	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		SPEA2	0.91	<0.001	0.4	<0.05	0.48	0.09	0.05	<0.001
		AbYSS	<0.01	<0.001	<0.01	<0.001	0.5	1	0.99	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	0.71	<0.001	0.36	<0.001	0.5	1	0.19	<0.001
		SMPSO	>0.99	<0.001	0.12	<0.001	0.3	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
	MoCell	SPEA2	>0.99	<0.001	>0.99	<0.001	0.48	0.09	<0.01	<0.001
		AbYSS	>0.99	<0.001	0.21	<0.001	0.5	1	0.02	<0.001
		CellIDE	0.69	<0.001	0.8	<0.001	0.5	1	0.83	<0.001
		GDE3	>0.99	<0.001	0.81	<0.05	0.5	1	<0.01	<0.001
		SMPSO	>0.99	<0.001	>0.99	<0.001	0.3	<0.001	<0.01	<0.001
		RS	0.26	<0.001	0.06	<0.001	0.5	1	>0.99	<0.001
		SPEA2	AbYSS	<0.01	<0.001	<0.01	<0.001	0.52	0.09	>0.99
	CellIDE	<0.01	<0.001	<0.01	<0.001	0.52	0.09	>0.99	<0.001	
	GDE3	0.16	<0.001	0.44	<0.05	0.52	0.09	0.85	<0.001	
	SMPSO	0.92	<0.001	0.15	<0.001	0.31	<0.001	<0.01	<0.001	
	RS	<0.01	<0.001	<0.01	<0.001	0.52	0.09	>0.99	<0.001	
	AbYSS	CellIDE	<0.01	<0.001	0.89	<0.001	0.5	1	>0.99	<0.001
		GDE3	>0.99	<0.001	0.81	<0.001	0.5	1	<0.01	<0.001
		SMPSO	>0.99	<0.001	>0.99	<0.001	0.3	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.35	<0.001	0.5	1	>0.99	<0.001
	CellIDE	GDE3	>0.99	<0.001	0.81	<0.05	0.5	1	<0.01	<0.001
		SMPSO	>0.99	<0.001	>0.99	<0.001	0.3	<0.001	<0.01	<0.001
		RS	0.18	<0.001	0.02	<0.001	0.5	1	>0.99	<0.001
	GDE3	SMPSO	>0.99	<0.001	0.3	0.06	0.3	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.19	<0.001	0.5	1	>0.99	<0.001
	SMPSO	RS	<0.01	<0.001	<0.01	<0.001	0.71	<0.001	>0.99	<0.001
S3	NSGA-II	NSGA-III	0.5	0.8	0.51	0.37	0.5	1	0.5	0.96
		MoCell	<0.01	<0.001	0.51	0.37	0.5	1	>0.99	<0.001
		SPEA2	0.98	<0.001	0.32	<0.001	0.49	0.17	0.03	<0.001
		AbYSS	<0.01	<0.001	0.51	0.37	0.5	1	>0.99	<0.001
		CellIDE	<0.01	<0.001	0.51	0.37	0.5	1	>0.99	<0.001
		GDE3	0.04	<0.001	0.51	0.37	0.5	1	0.96	<0.001
		SMPSO	>0.99	<0.001	0.12	<0.001	0.38	<0.001	<0.01	<0.001
	RS	<0.01	<0.001	0.51	0.37	0.5	1	>0.99	<0.001	
	NSGA-III	MoCell	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SPEA2	0.98	<0.001	0.31	<0.001	0.49	0.17	0.03	<0.001
		AbYSS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		CellIDE	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		GDE3	0.03	<0.001	0.5	1	0.5	1	0.97	<0.001
		SMPSO	>0.99	<0.001	0.12	<0.001	0.38	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	MoCell	SPEA2	>0.99	<0.001	0.31	<0.001	0.49	0.17	<0.01	<0.001
		AbYSS	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		CellIDE	0.45	0.18	0.5	1	0.5	1	0.55	0.18

		GDE3	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001	
		SMPSO	>0.99	<0.001	0.12	<0.001	0.38	<0.001	<0.01	<0.001	
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001	
	SPEA2	AbYSS	<0.01	<0.001	0.69	<0.001	0.52	0.17	>0.99	<0.001	
		CellIDE	<0.01	<0.001	0.69	<0.001	0.52	0.17	>0.99	<0.001	
		GDE3	<0.01	<0.001	0.69	<0.001	0.52	0.17	>0.99	<0.001	
		SMPSO	0.94	<0.001	0.23	<0.001	0.39	<0.001	<0.01	<0.001	
		RS	<0.01	<0.001	0.69	<0.001	0.52	0.17	>0.99	<0.001	
		AbYSS	CellIDE	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	GDE3		0.94	<0.001	0.5	1	0.5	1	0.06	<0.001	
	SMPSO		>0.99	<0.001	0.12	<0.001	0.38	<0.001	<0.01	<0.001	
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001	
		CellIDE	GDE3	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
			SMPSO	>0.99	<0.001	0.12	<0.001	0.38	<0.001	<0.01	<0.001
	RS		<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001	
	GDE3	SMPSO	>0.99	<0.001	0.12	<0.001	0.38	<0.001	<0.01	<0.001	
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001	
		SMPSO	RS	<0.01	<0.001	0.88	<0.001	0.63	<0.001	>0.99	<0.001
S4	NSGA-II	NSGA-III	0.55	0.15	0.53	0.34	0.48	0.18	0.43	0.24	
		MoCell	<0.01	<0.001	<0.01	<0.001	0.53	<0.05	>0.99	<0.001	
		SPEA2	0.99	<0.001	0.96	<0.001	0.34	<0.001	0.01	<0.001	
		AbYSS	0.23	<0.001	<0.01	<0.001	0.53	<0.05	>0.99	<0.001	
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.53	<0.05	>0.99	<0.001	
		GDE3	0.6	<0.05	0.37	<0.001	0.48	0.24	0.34	<0.001	
		SMPSO	>0.99	<0.001	0.49	0.72	0.11	<0.001	<0.01	<0.001	
		RS	<0.01	<0.001	<0.01	<0.001	0.53	<0.05	>0.99	<0.001	
	NSGA-III	MoCell	<0.01	<0.001	<0.01	<0.001	0.55	<0.05	>0.99	<0.001	
		SPEA2	0.98	<0.001	0.92	<0.001	0.36	<0.001	0.02	<0.001	
		AbYSS	0.18	<0.001	<0.01	<0.001	0.55	<0.05	>0.99	<0.001	
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.55	<0.05	>0.99	<0.001	
		GDE3	0.54	0.16	0.34	<0.001	0.5	0.67	0.46	0.15	
		SMPSO	>0.99	<0.001	0.48	0.81	0.12	<0.001	<0.01	<0.001	
		RS	<0.01	<0.001	<0.01	<0.001	0.55	<0.05	>0.99	<0.001	
		MoCell	SPEA2	>0.99	<0.001	>0.99	<0.001	0.32	<0.001	<0.01	<0.001
	MoCell	AbYSS	>0.99	<0.001	0.38	<0.05	0.5	1	0.02	<0.001	
		CellIDE	0.15	<0.001	0.07	<0.001	0.5	1	0.84	<0.001	
		GDE3	>0.99	<0.001	>0.99	<0.001	0.46	<0.05	<0.01	<0.001	
		SMPSO	>0.99	<0.001	0.7	<0.001	0.11	<0.001	<0.01	<0.001	
		RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001	
		SPEA2	AbYSS	<0.01	<0.001	<0.01	<0.001	0.68	<0.001	>0.99	<0.001
			CellIDE	<0.01	<0.001	<0.01	<0.001	0.68	<0.001	>0.99	<0.001
			GDE3	<0.01	<0.001	<0.01	<0.001	0.64	<0.001	>0.99	<0.001
	SMPSO		>0.99	<0.001	0.38	<0.05	0.17	<0.001	0.1	<0.001	
		RS	<0.01	<0.001	<0.01	<0.001	0.68	<0.001	>0.99	<0.001	
		AbYSS	CellIDE	<0.01	<0.001	0.27	<0.001	0.5	1	>0.99	<0.001
			GDE3	0.92	<0.001	>0.99	<0.001	0.46	<0.05	<0.01	<0.001
			SMPSO	>0.99	<0.001	0.72	<0.001	0.11	<0.001	<0.01	<0.001
	RS		<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001	
	CellIDE	GDE3	>0.99	<0.001	>0.99	<0.001	0.46	<0.05	<0.01	<0.001	
		SMPSO	>0.99	<0.001	0.74	<0.001	0.11	<0.001	<0.01	<0.001	
		RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001	
		GDE3	SMPSO	>0.99	<0.001	0.51	0.33	0.12	<0.001	<0.01	<0.001
	RS		<0.01	<0.001	<0.01	<0.001	0.55	<0.05	>0.99	<0.001	
	SMPSO	RS	<0.01	<0.001	0.11	<0.001	0.9	<0.001	>0.99	<0.001	
S5	NSGA-II	NSGA-III	0.35	<0.001	0.53	<0.05	0.53	<0.05	0.62	<0.05	
		MoCell	<0.01	<0.001	0.53	<0.05	0.53	<0.05	>0.99	<0.001	
		SPEA2	0.97	<0.001	0.36	<0.001	0.34	<0.001	0.03	<0.001	
		AbYSS	<0.01	<0.001	0.53	<0.05	0.53	<0.05	>0.99	<0.001	
		CellIDE	<0.01	<0.001	0.53	<0.05	0.53	<0.05	>0.99	<0.001	
		GDE3	0.03	<0.001	0.53	<0.05	0.53	<0.05	0.97	<0.001	
		SMPSO	>0.99	<0.001	0.14	<0.001	0.13	<0.001	<0.01	<0.001	
		RS	<0.01	<0.001	0.53	<0.05	0.53	<0.05	>0.99	<0.001	
	NSGA-III	MoCell	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001	
		SPEA2	>0.99	<0.001	0.34	<0.001	0.33	<0.001	0.01	<0.001	
		AbYSS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001	
		CellIDE	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001	
		GDE3	0.05	<0.001	0.5	1	0.5	1	0.95	<0.001	
		SMPSO	>0.99	<0.001	0.13	<0.001	0.13	<0.001	<0.01	<0.001	
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001	
		MoCell	SPEA2	>0.99	<0.001	0.34	<0.001	0.33	<0.001	<0.01	<0.001
	MoCell	AbYSS	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001	
		CellIDE	0.45	0.4	0.5	1	0.5	1	0.55	0.37	
		GDE3	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001	
		SMPSO	>0.99	<0.001	0.13	<0.001	0.13	<0.001	<0.01	<0.001	
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001	
	SPEA2	AbYSS	<0.01	<0.001	0.66	<0.001	0.68	<0.001	>0.99	<0.001	
		CellIDE	<0.01	<0.001	0.66	<0.001	0.68	<0.001	>0.99	<0.001	

		GDE3	<0.01	<0.001	0.66	<0.001	0.68	<0.001	>0.99	<0.001
		SMPSO	0.97	<0.001	0.22	<0.001	0.21	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.66	<0.001	0.68	<0.001	>0.99	<0.001
	AbYSS	CellIDE	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		GDE3	0.97	<0.001	0.5	1	0.5	1	0.03	<0.001
		SMPSO	>0.99	<0.001	0.13	<0.001	0.13	<0.001	<0.01	<0.001
	CellIDE	RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		GDE3	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.13	<0.001	0.13	<0.001	<0.01	<0.001
	GDE3	RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.13	<0.001	0.13	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	SMPSO	RS	<0.01	<0.001	0.88	<0.001	0.88	<0.001	>0.99	<0.001

A.1.3 Results of Rank Values and Confidence Values

TABLE A-3 Rank values and confidence values for each objectives of each strategy (AW1)

Str	Algorithms	Rank Value				Confidence Value			
		PTM	O2 of Si	PTR	HV	PTM	O2 of Si	PTR	HV
S2	NSGA-II	5	7	2	5	11.1%	17.5%	11.8%	12.2%
	NSGA-III	6	7	2	5	13.3%	17.5%	11.8%	12.2%
	MoCell	2	3	2	3	4.4%	7.5%	11.8%	7.3%
	SPEA2	8	6	2	7	17.8%	15.0%	11.8%	17.1%
	AbYSS	4	2	2	4	8.9%	5.0%	11.8%	9.8%
	CellIDE	3	4	2	2	6.7%	10.0%	11.8%	4.9%
	GDE3	7	5	2	6	15.6%	12.5%	11.8%	14.6%
	SMPSO	9	5	1	8	20.0%	12.5%	5.9%	19.5%
S3	RS	1	1	2	1	2.2%	2.5%	11.8%	2.4%
	NSGA-II	4	3	2	4	14.8%	12.5%	11.8%	14.8%
	NSGA-III	4	3	2	4	14.8%	12.5%	11.8%	14.8%
	MoCell	1	3	2	1	3.7%	12.5%	11.8%	3.7%
	SPEA2	5	2	2	5	18.5%	8.3%	11.8%	18.5%
	AbYSS	2	3	2	2	7.4%	12.5%	11.8%	7.4%
	CellIDE	1	3	2	1	3.7%	12.5%	11.8%	3.7%
	GDE3	3	3	2	3	11.1%	12.5%	11.8%	11.1%
S4	SMPSO	6	1	1	6	22.2%	4.2%	5.9%	22.2%
	RS	1	3	2	1	3.7%	12.5%	11.8%	3.7%
	NSGA-II	4	5	3	4	12.1%	16.1%	10.7%	12.1%
	NSGA-III	4	5	3	4	12.1%	16.1%	10.7%	12.1%
	MoCell	2	3	4	2	6.1%	9.7%	14.3%	6.1%
	SPEA2	6	6	2	6	18.2%	19.4%	7.1%	18.2%
	AbYSS	3	2	4	3	9.1%	6.5%	14.3%	9.1%
	CellIDE	1	1	4	1	3.0%	3.2%	14.3%	3.0%
S5	GDE3	5	4	3	5	15.2%	12.9%	10.7%	15.2%
	SMPSO	7	4	1	7	21.2%	12.9%	3.6%	21.2%
	RS	1	1	4	1	3.0%	3.2%	14.3%	3.0%
	NSGA-II	5	3	3	5	16.7%	10.0%	10.0%	16.7%
	NSGA-III	4	4	4	4	13.3%	13.3%	13.3%	13.3%
	MoCell	1	4	4	1	3.3%	13.3%	13.3%	3.3%
	SPEA2	6	2	2	6	20.0%	6.7%	6.7%	20.0%
	AbYSS	2	4	4	2	6.7%	13.3%	13.3%	6.7%
	CellIDE	1	4	4	1	3.3%	13.3%	13.3%	3.3%
	GDE3	3	4	4	3	10.0%	13.3%	13.3%	10.0%
	SMPSO	7	1	1	7	23.3%	3.3%	3.3%	23.3%
	RS	1	4	4	1	3.3%	13.3%	13.3%	3.3%

A.2 AW2

A.2.1 Kruskal–Wallis Test

TABLE A-4 Kruskal–Wallis Test for each objective of each strategy (AW2)

Str.	PTM		O2 of Si		PTR		HV	
	DF	Prob> ChiSq	DF	Prob> ChiSq	DF	Prob> ChiSq	DF	Prob> ChiSq
S2	8	<.0001	8	<.0001	8	<.0001	8	<.0001
S3	8	<.0001	8	<.0001	8	<.0001	8	<.0001
S4	8	<.0001	8	<.0001	8	<.0001	8	<.0001
S5	8	<.0001	8	<.0001	8	<.0001	8	<.0001

A.2.2 Mann-Whitney U Test and Vargha and Delaney statistics

TABLE A-5 Mann-Whitney U Test and Vargha and Delaney statistics for each objective of each strategy (AW2)

Str	Algorithm A	Algorithm B	PTM		O2 of S_i		PTR		HV	
			A_{12}	p-value	A_{12}	p-value	A_{12}	p-value	A_{12}	p-value
S2	NSGA-II	NSGA-III	0.66	0.66	0.81	<0.001	0.5	1	0.29	<0.001
		MoCell	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		SPEA2	0.95	0.95	0.93	<0.001	0.5	1	<0.01	<0.001
		AbYSS	>0.99	>0.99	<0.01	<0.001	0.5	1	0.02	<0.001
		CellDE	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	0.21	0.21	0.01	<0.001	0.5	1	0.6	<0.05
		SMP SO	>0.99	>0.99	0.46	0.09	0.22	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		MoCell	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		SPEA2	0.9	0.9	0.77	<0.001	0.5	1	0.02	<0.001
	NSGA-III	AbYSS	0.99	0.99	<0.01	<0.001	0.5	1	0.08	<0.001
		CellDE	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	0.1	0.1	<0.01	<0.001	0.5	1	0.84	<0.001
		SMP SO	>0.99	>0.99	0.38	<0.05	0.22	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		SPEA2	>0.99	>0.99	>0.99	<0.001	0.5	1	<0.01	<0.001
		AbYSS	>0.99	>0.99	0.28	<0.001	0.5	1	<0.01	<0.001
		CellDE	0.17	0.17	0.1	<0.001	0.5	1	0.67	<0.001
		GDE3	>0.99	>0.99	>0.99	<0.001	0.5	1	<0.01	<0.001
		SMP SO	>0.99	>0.99	0.79	<0.001	0.22	<0.001	<0.01	<0.001
	MoCell	RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		AbYSS	>0.99	>0.99	>0.99	<0.001	0.5	1	<0.01	<0.001
		CellDE	0.17	0.17	0.1	<0.001	0.5	1	0.67	<0.001
		GDE3	>0.99	>0.99	>0.99	<0.001	0.5	1	<0.01	<0.001
		SMP SO	>0.99	>0.99	0.79	<0.001	0.22	<0.001	<0.01	<0.001
	SPEA2	RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		AbYSS	0.6	0.6	<0.01	<0.001	0.5	1	0.89	<0.001
		CellDE	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		SMP SO	>0.99	>0.99	0.32	<0.001	0.22	<0.001	<0.01	<0.001
	AbYSS	RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		CellDE	<0.01	<0.01	0.26	<0.001	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.01	>0.99	<0.001	0.5	1	>0.99	<0.001
		SMP SO	>0.99	>0.99	0.82	<0.001	0.22	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
	CellDE	GDE3	>0.99	>0.99	>0.99	<0.001	0.5	1	<0.01	<0.001
		SMP SO	>0.99	>0.99	0.85	<0.001	0.22	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	>0.99	>0.99	0.62	0.11	0.22	<0.001	<0.01	<0.001
	GDE3	RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		SMP SO	>0.99	>0.99	0.62	0.11	0.22	<0.001	<0.01	<0.001
	SMP SO	RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		RS	<0.01	<0.01	0.1	<0.001	0.79	<0.001	>0.99	<0.001
S3	NSGA-II	NSGA-III	0.47	0.47	0.5	1	0.5	1	0.53	0.42
		MoCell	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		SPEA2	>0.99	>0.99	0.5	1	0.5	1	<0.01	<0.001
		AbYSS	0.02	0.02	0.5	1	0.5	1	0.98	<0.001
		CellDE	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		SMP SO	>0.99	>0.99	0.14	<0.001	0.2	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		MoCell	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		SPEA2	>0.99	>0.99	0.5	1	0.5	1	<0.01	<0.001
	NSGA-III	AbYSS	0.02	0.02	0.5	1	0.5	1	0.98	<0.001
		CellDE	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		SMP SO	>0.99	>0.99	0.14	<0.001	0.2	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		SPEA2	>0.99	>0.99	0.5	1	0.5	1	<0.01	<0.001
		AbYSS	>0.99	>0.99	0.5	1	0.5	1	<0.01	<0.001
		CellDE	0.13	0.13	0.5	1	0.5	1	0.87	<0.001
		GDE3	>0.99	>0.99	0.5	1	0.5	1	<0.01	<0.001
		SMP SO	>0.99	>0.99	0.14	<0.001	0.2	<0.001	<0.01	<0.001
	MoCell	RS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		AbYSS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		CellDE	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		SMP SO	>0.99	>0.99	0.14	<0.001	0.2	<0.001	<0.01	<0.001
	SPEA2	RS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		AbYSS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		CellDE	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		SMP SO	>0.99	>0.99	0.14	<0.001	0.2	<0.001	<0.01	<0.001
	AbYSS	RS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		CellDE	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		SMP SO	>0.99	>0.99	0.14	<0.001	0.2	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
	CellDE	GDE3	>0.99	>0.99	0.5	1	0.5	1	<0.01	<0.001
		SMP SO	>0.99	>0.99	0.14	<0.001	0.2	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		GDE3	>0.99	>0.99	0.5	1	0.5	1	<0.01	<0.001
	GDE3	SMP SO	>0.99	>0.99	0.14	<0.001	0.2	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001

S4	SMPSO	RS	<0.01	<0.01	0.86	<0.001	0.8	<0.001	>0.99	<0.001
	NSGA-II	NSGA-III	0.46	0.46	0.27	<0.001	0.5	1	0.49	0.97
		MoCell	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		SPEA2	>0.99	>0.99	0.96	<0.001	0.5	1	<0.01	<0.001
		AbYSS	0.33	0.33	<0.01	<0.001	0.5	1	0.98	<0.001
		CellDE	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	0.03	0.03	<0.01	<0.001	0.5	1	>0.99	<0.001
		SMPSO	>0.99	>0.99	0.49	<0.001	0.15	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
	NSGA-III	MoCell	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		SPEA2	>0.99	>0.99	0.98	<0.001	0.5	1	<0.01	<0.001
		AbYSS	0.41	0.41	0.04	<0.001	0.5	1	0.99	<0.001
		CellDE	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	0.02	0.02	0.06	<0.001	0.5	1	>0.99	<0.001
		SMPSO	>0.99	>0.99	0.53	<0.001	0.15	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
	MoCell	SPEA2	>0.99	>0.99	>0.99	<0.001	0.5	1	<0.01	<0.001
		AbYSS	>0.99	>0.99	0.96	<0.001	0.5	1	<0.01	<0.001
		CellDE	0.05	0.05	0.01	<0.001	0.5	1	0.96	<0.001
		GDE3	>0.99	>0.99	>0.99	<0.001	0.5	1	<0.01	<0.001
		SMPSO	>0.99	>0.99	0.59	<0.001	0.15	<0.001	<0.01	<0.001
	SPEA2	RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		AbYSS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		CellDE	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
	AbYSS	SMPSO	>0.99	>0.99	0.46	<0.05	0.15	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		CellDE	<0.01	<0.01	0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.01	0.73	<0.001	0.5	1	0.45	0.46
	CellDE	SMPSO	>0.99	>0.99	0.58	<0.001	0.15	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	>0.99	>0.99	>0.99	<0.001	0.5	1	<0.01	<0.001
		SMPSO	>0.99	>0.99	0.7	<0.001	0.15	<0.001	<0.01	<0.001
	GDE3	RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
		SMPSO	>0.99	>0.99	0.57	<0.001	0.15	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	<0.01	<0.001	0.5	1	>0.99	<0.001
	SMPSO	RS	<0.01	<0.01	0.2	<0.001	0.86	<0.001	>0.99	<0.001
S5	NSGA-II	NSGA-III	0.55	0.55	0.5	1	0.5	1	0.45	0.23
		MoCell	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		SPEA2	>0.99	>0.99	0.5	1	0.5	1	<0.01	<0.001
		AbYSS	0.03	0.03	0.5	1	0.5	1	0.97	<0.001
		CellDE	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		SMPSO	>0.99	>0.99	0.16	<0.001	0.12	<0.001	<0.01	<0.001
	NSGA-III	RS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		MoCell	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		SPEA2	>0.99	>0.99	0.5	1	0.5	1	<0.01	<0.001
		AbYSS	0.01	0.01	0.5	1	0.5	1	0.99	<0.001
		CellDE	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		SMPSO	>0.99	>0.99	0.16	<0.001	0.12	<0.001	<0.01	<0.001
	MoCell	RS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		SPEA2	>0.99	>0.99	0.5	1	0.5	1	<0.01	<0.001
		AbYSS	>0.99	>0.99	0.5	1	0.5	1	<0.01	<0.001
		CellDE	0.18	0.18	0.5	1	0.5	1	0.82	<0.001
		GDE3	>0.99	>0.99	0.5	1	0.5	1	<0.01	<0.001
	SPEA2	SMPSO	>0.99	>0.99	0.16	<0.001	0.12	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		AbYSS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		CellDE	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
	AbYSS	GDE3	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		SMPSO	>0.99	>0.99	0.16	<0.001	0.12	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
		CellDE	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
	CellDE	GDE3	>0.99	>0.99	0.5	1	0.5	1	<0.01	<0.001
		SMPSO	>0.99	>0.99	0.16	<0.001	0.12	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
	GDE3	SMPSO	>0.99	>0.99	0.16	<0.001	0.12	<0.001	<0.01	<0.001
		RS	<0.01	<0.01	0.5	1	0.5	1	>0.99	<0.001
	SMPSO	RS	<0.01	<0.01	0.84	<0.001	0.89	<0.001	>0.99	<0.001

A.2.3 Results of Rank Values and Confidence Values

TABLE A-6 Rank values and confidence values for each objectives of each strategy (AW2)

Str	Algorithms	Rank Value				Confidence Value			
		PTM	O2 of Si	PTR	HV	PTM	O2 of Si	PTR	HV
S2	NSGA-II	4	5	2	4	10.8%	15.2%	11.8%	10.8%
	NSGA-III	5	6	2	5	13.5%	18.2%	11.8%	13.5%
	MoCell	2	3	2	2	5.4%	9.1%	11.8%	5.4%
	SPEA2	6	7	2	7	16.2%	21.2%	11.8%	18.9%
	AbYSS	7	2	2	6	18.9%	6.1%	11.8%	16.2%
	CellDE	1	1	2	1	2.7%	3.0%	11.8%	2.7%
	GDE3	3	4	2	3	8.1%	12.1%	11.8%	8.1%
	SMPISO	8	4	1	8	21.6%	12.1%	5.9%	21.6%
S3	RS	1	1	2	1	2.7%	3.0%	11.8%	2.7%
	NSGA-II	5	2	2	5	14.7%	11.8%	11.8%	14.7%
	NSGA-III	5	2	2	5	14.7%	11.8%	11.8%	14.7%
	MoCell	2	2	2	2	5.9%	11.8%	11.8%	5.9%
	SPEA2	6	2	2	6	17.6%	11.8%	11.8%	17.6%
	AbYSS	4	2	2	4	11.8%	11.8%	11.8%	11.8%
	CellDE	1	2	2	1	2.9%	11.8%	11.8%	2.9%
	GDE3	3	2	2	3	8.8%	11.8%	11.8%	8.8%
S4	SMPISO	7	1	1	7	20.6%	5.9%	5.9%	20.6%
	RS	1	2	2	1	2.9%	11.8%	11.8%	2.9%
	NSGA-II	5	7	2	4	14.7%	18.9%	11.8%	13.8%
	NSGA-III	5	5	2	4	14.7%	13.5%	11.8%	13.8%
	MoCell	2	2	2	2	5.9%	5.4%	11.8%	6.9%
	SPEA2	6	8	2	5	17.6%	21.6%	11.8%	17.2%
	AbYSS	4	3	2	3	11.8%	8.1%	11.8%	10.3%
	CellDE	1	1	2	1	2.9%	2.7%	11.8%	3.4%
S5	GDE3	3	4	2	3	8.8%	10.8%	11.8%	10.3%
	SMPISO	7	6	1	6	20.6%	16.2%	5.9%	20.7%
	RS	1	1	2	1	2.9%	2.7%	11.8%	3.4%
	NSGA-II	5	2	2	5	14.7%	11.8%	11.8%	14.7%
	NSGA-III	5	2	2	5	14.7%	11.8%	11.8%	14.7%
	MoCell	2	2	2	2	5.9%	11.8%	11.8%	5.9%
	SPEA2	6	2	2	6	17.6%	11.8%	11.8%	17.6%
	AbYSS	4	2	2	4	11.8%	11.8%	11.8%	11.8%
S5	CellDE	1	2	2	1	2.9%	11.8%	11.8%	2.9%
	GDE3	3	2	2	3	8.8%	11.8%	11.8%	8.8%
	SMPISO	7	1	1	7	20.6%	5.9%	5.9%	20.6%
	RS	1	2	2	1	2.9%	11.8%	11.8%	2.9%

A.3 AW3

A.3.1 Kruskal–Wallis Test

TABLE A-7 Kruskal–Wallis Test for each objective of each strategy (AW3)

Str.	PTM		O2 of Si		PTR		HV	
	DF	Prob> ChiSq	DF	Prob> ChiSq	DF	Prob> ChiSq	DF	Prob> ChiSq
S2	8	<.0001	8	<.0001	8	<.0001	8	<.0001
S3	8	<.0001	8	<.0001	8	<.0001	8	<.0001
S4	8	<.0001	8	<.0001	8	<.0001	8	<.0001
S5	8	<.0001	8	<.0001	8	<.0001	8	<.0001

A.3.2 Mann-Whitney U Test and Vargha and Delaney statistics

TABLE A-8 Mann-Whitney U Test and Vargha and Delaney statistics for each objective of each strategy (AW3)

Str	Algorithm A	Algorithm B	PTM		O2 of Si		PTR		HV	
			\hat{A}_{12}	p-value	\hat{A}_{12}	p-value	\hat{A}_{12}	p-value	\hat{A}_{12}	p-value
S2	NSGA-II	NSGA-III	0.34	<0.001	0.34	<0.05	0.5	1	0.22	<0.001
		MoCell	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		SPEA2	0.93	<0.001	0.71	<0.001	0.5	1	<0.01	<0.001
		AbYSS	>0.99	<0.001	<0.01	<0.001	0.5	1	<0.01	<0.001
		CellDE	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	0.19	<0.001	0.22	<0.001	0.5	1	0.56	0.15
		SMPISO	>0.99	<0.001	0.87	<0.001	0.29	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
	NSGA-III	MoCell	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		SPEA2	0.95	<0.001	0.85	<0.001	0.5	1	0.03	<0.001
		AbYSS	>0.99	<0.001	<0.01	<0.001	0.5	1	0.02	<0.001

		AbYSS	>0.99	<0.001	0.45	0.16	0.5	1	<0.01	<0.001
		CellIDE	0.02	<0.001	<0.01	<0.001	0.5	1	0.96	<0.001
		GDE3	>0.99	<0.001	>0.99	<0.001	0.5	1	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.81	<0.001	0.15	<0.001	<0.01	<0.001
	SPEA2	RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		AbYSS	0.04	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
	AbYSS	SMPSO	>0.99	<0.001	0.61	<0.001	0.15	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		CellIDE	<0.01	<0.001	0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.001	>0.99	<0.001	0.5	1	0.91	<0.001
	CellIDE	SMPSO	>0.99	<0.001	0.81	<0.001	0.15	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	>0.99	<0.001	>0.99	<0.001	0.5	1	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.81	<0.001	0.15	<0.001	<0.01	<0.001
	GDE3	RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.76	<0.001	0.15	<0.001	<0.01	<0.001
	SMPSO	RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		RS	<0.01	<0.001	0.14	<0.001	0.86	<0.001	>0.99	<0.001
S5	NSGA-II	NSGA-III	0.53	0.27	0.5	1	0.5	1	0.47	0.29
		MoCell	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SPEA2	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		AbYSS	0.03	<0.001	0.5	1	0.5	1	0.97	<0.001
		CellIDE	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.13	<0.001	0.13	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	NSGA-III	MoCell	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SPEA2	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		AbYSS	0.03	<0.001	0.5	1	0.5	1	0.97	<0.001
		CellIDE	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.13	<0.001	0.13	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		MoCell	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	MoCell	SPEA2	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		AbYSS	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		CellIDE	0.12	<0.001	0.5	1	0.5	1	0.88	<0.001
		GDE3	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.13	<0.001	0.13	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	SPEA2	AbYSS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		CellIDE	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.13	<0.001	0.13	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	AbYSS	CellIDE	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.13	<0.001	0.13	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	CellIDE	GDE3	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.13	<0.001	0.13	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	GDE3	SMPSO	>0.99	<0.001	0.13	<0.001	0.13	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	SMPSO	RS	<0.01	<0.001	0.88	<0.001	0.88	<0.001	>0.99	<0.001

A.3.3 Results of Rank Values and Confidence Values

TABLE A-9 Rank values and confidence values for each objectives of each strategy (AW3)

Str	Algorithms	Rank Value				Confidence Value			
		PTM	O2 of Si	PTR	HV	PTM	O2 of Si	PTR	HV
S2	NSGA-II	5	5	2	4	13.5%	16.1%	11.8%	10.5%
	NSGA-III	4	4	2	5	10.8%	12.9%	11.8%	13.2%
	MoCell	2	2	2	3	5.4%	6.5%	11.8%	7.9%
	SPEA2	6	6	2	6	16.2%	19.4%	11.8%	15.8%
	AbYSS	7	1	2	6	18.9%	3.2%	11.8%	15.8%
	CellIDE	1	2	2	2	2.7%	6.5%	11.8%	5.3%
	GDE3	3	3	2	4	8.1%	9.7%	11.8%	10.5%
	SMPSO	8	7	1	7	21.6%	22.6%	5.9%	18.4%
S3	RS	1	1	2	1	2.7%	3.2%	11.8%	2.6%
	NSGA-II	5	2	2	5	14.7%	11.8%	11.8%	14.7%
	NSGA-III	5	2	2	5	14.7%	11.8%	11.8%	14.7%
	MoCell	2	2	2	2	5.9%	11.8%	11.8%	5.9%

	SPEA2	6	2	2	6	17.6%	11.8%	11.8%	17.6%
	AbYSS	4	2	2	4	11.8%	11.8%	11.8%	11.8%
	CellIDE	1	2	2	1	2.9%	11.8%	11.8%	2.9%
	GDE3	3	2	2	3	8.8%	11.8%	11.8%	8.8%
	SMPSO	7	1	1	7	20.6%	5.9%	5.9%	20.6%
	RS	1	2	2	1	2.9%	11.8%	11.8%	2.9%
	NSGA-II	5	5	2	5	13.5%	16.1%	11.8%	14.7%
	NSGA-III	4	4	2	5	10.8%	12.9%	11.8%	14.7%
	MoCell	2	2	2	2	5.4%	6.5%	11.8%	5.9%
	SPEA2	7	6	2	6	18.9%	19.4%	11.8%	17.6%
S4	AbYSS	6	2	2	4	16.2%	6.5%	11.8%	11.8%
	CellIDE	1	1	2	1	2.7%	3.2%	11.8%	2.9%
	GDE3	3	3	2	3	8.1%	9.7%	11.8%	8.8%
	SMPSO	8	7	1	7	21.6%	22.6%	5.9%	20.6%
	RS	1	1	2	1	2.7%	3.2%	11.8%	2.9%
	NSGA-II	5	2	2	5	14.7%	11.8%	11.8%	14.7%
	NSGA-III	5	2	2	5	14.7%	11.8%	11.8%	14.7%
	MoCell	2	2	2	2	5.9%	11.8%	11.8%	5.9%
S5	SPEA2	6	2	2	6	17.6%	11.8%	11.8%	17.6%
	AbYSS	4	2	2	4	11.8%	11.8%	11.8%	11.8%
	CellIDE	1	2	2	1	2.9%	11.8%	11.8%	2.9%
	GDE3	3	2	2	3	8.8%	11.8%	11.8%	8.8%
	SMPSO	7	1	1	7	20.6%	5.9%	5.9%	20.6%
	RS	1	2	2	1	2.9%	11.8%	11.8%	2.9%

A.4 AW4

A.4.1 Kruskal–Wallis Test

TABLE A-10 Kruskal–Wallis Test for each objective of each strategy (AW4)

Str.	PTM		O2 of Si		PTR		HV	
	DF	Prob> ChiSq	DF	Prob> ChiSq	DF	Prob> ChiSq	DF	Prob> ChiSq
S2	8	<.0001	8	<.0001	8	<.0001	8	<.0001
S3	8	<.0001	8	<.0001	8	<.0001	8	<.0001
S4	8	<.0001	8	<.0001	8	<.0001	8	<.0001
S5	8	<.0001	8	<.0001	8	<.0001	8	<.0001

A.4.2 Mann-Whitney U Test and Vargha and Delaney statistics

TABLE A-11 Mann-Whitney U Test and Vargha and Delaney statistics for each objective of each strategy (AW4)

Str	Algorithm A	Algorithm B	PTM		O2 of Si		PTR		HV	
			\hat{A}_{12}	p-value	\hat{A}_{12}	p-value	\hat{A}_{12}	p-value	\hat{A}_{12}	p-value
S2	NSGA-II	NSGA-III	0.47	0.51	0.64	<0.05	0.7	<0.001	0.53	0.61
		MoCell	<0.01	<0.001	<0.01	<0.001	0.7	<0.001	>0.99	<0.001
		SPEA2	0.9	<0.001	>0.99	<0.001	0.55	0.13	0.09	<0.001
		AbYSS	0.52	0.6	<0.01	<0.001	0.59	<0.05	0.79	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.82	<0.001	>0.99	<0.001
		GDE3	0.68	<0.001	0.95	<0.001	0.62	<0.001	0.16	<0.001
		SMPSO	0.92	<0.001	0.14	<0.001	0.63	<0.05	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.82	<0.001	>0.99	<0.001
	NSGA-III	MoCell	<0.01	<0.001	<0.01	<0.001	0.48	0.98	>0.99	<0.001
		SPEA2	0.92	<0.001	>0.99	<0.001	0.33	<0.001	0.08	<0.001
		AbYSS	0.57	<0.05	<0.01	<0.001	0.38	<0.05	0.78	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.65	<0.001	>0.99	<0.001
		GDE3	0.72	<0.001	0.95	<0.001	0.39	<0.05	0.13	<0.001
		SMPSO	0.92	<0.001	0.14	<0.001	0.42	<0.05	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.65	<0.001	>0.99	<0.001
	MoCell	SPEA2	>0.99	<0.001	>0.99	<0.001	0.34	<0.001	<0.01	<0.001
		AbYSS	>0.99	<0.001	0.39	<0.05	0.39	<0.001	<0.01	<0.001
		CellIDE	0.45	0.13	0.14	<0.001	0.67	<0.001	0.42	0.07
		GDE3	>0.99	<0.001	0.99	<0.001	0.41	<0.05	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.25	<0.001	0.44	<0.05	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.67	<0.001	>0.99	<0.001
	SPEA2	AbYSS	0.08	<0.001	<0.01	<0.001	0.55	0.31	0.99	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.81	<0.001	>0.99	<0.001
		GDE3	0.23	<0.001	0.76	<0.001	0.58	<0.05	0.75	<0.001
		SMPSO	0.84	<0.001	0.13	<0.001	0.59	0.11	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.81	<0.001	>0.99	<0.001
	AbYSS	CellIDE	<0.01	<0.001	0.26	<0.001	0.76	<0.001	>0.99	<0.001
		GDE3	0.69	<0.001	0.99	<0.001	0.52	0.07	0.02	<0.001
		SMPSO	0.92	<0.001	0.27	<0.001	0.54	0.54	<0.01	<0.001

	CellIDE	RS	<0.01	<0.001	<0.01	<0.001	0.76	<0.001	>0.99	<0.001
		GDE3	>0.99	<0.001	>0.99	<0.001	0.24	<0.001	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.37	<0.001	0.29	<0.001	<0.01	<0.001
	GDE3	RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		SMPSO	0.89	<0.001	0.13	<0.001	0.52	0.34	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.76	<0.001	>0.99	<0.001
	SMPSO	RS	<0.01	<0.001	0.19	<0.001	0.71	<0.001	>0.99	<0.001
S3	NSGA-II	NSGA-III	0.48	0.79	0.43	0.09	0.5	1	0.5	0.95
		MoCell	<0.01	<0.001	0.67	<0.001	0.5	1	>0.99	<0.001
		SPEA2	0.96	<0.001	0.33	<0.001	0.47	<0.05	0.03	<0.001
		AbYSS	<0.01	<0.001	0.63	<0.001	0.5	1	>0.99	<0.001
		CellIDE	<0.01	<0.001	0.68	<0.001	0.5	1	>0.99	<0.001
		GDE3	0.77	<0.001	0.45	0.14	0.5	1	0.19	<0.001
		SMPSO	>0.99	<0.001	0.23	<0.001	0.38	<0.001	<0.01	<0.001
	NSGA-III	RS	<0.01	<0.001	0.68	<0.001	0.5	1	>0.99	<0.001
		MoCell	<0.01	<0.001	0.74	<0.001	0.5	1	>0.99	<0.001
		SPEA2	0.97	<0.001	0.39	<0.001	0.47	<0.05	0.03	<0.001
		AbYSS	<0.01	<0.001	0.69	<0.001	0.5	1	>0.99	<0.001
		CellIDE	<0.01	<0.001	0.75	<0.001	0.5	1	>0.99	<0.001
		GDE3	0.79	<0.001	0.52	0.84	0.5	1	0.19	<0.001
		SMPSO	>0.99	<0.001	0.28	<0.001	0.38	<0.001	<0.01	<0.001
	MoCell	RS	<0.01	<0.001	0.75	<0.001	0.5	1	>0.99	<0.001
		SPEA2	>0.99	<0.001	0.19	<0.001	0.47	<0.05	<0.01	<0.001
		AbYSS	>0.99	<0.001	0.45	<0.05	0.5	1	<0.01	<0.001
		CellIDE	0.7	<0.001	0.51	0.35	0.5	1	0.3	<0.001
		GDE3	>0.99	<0.001	0.28	<0.001	0.5	1	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.13	<0.001	0.38	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.51	0.35	0.5	1	>0.99	<0.001
	SPEA2	AbYSS	<0.01	<0.001	0.78	<0.001	0.53	<0.05	>0.99	<0.001
		CellIDE	<0.01	<0.001	0.82	<0.001	0.53	<0.05	>0.99	<0.001
		GDE3	0.11	<0.001	0.63	<0.001	0.53	<0.05	0.92	<0.001
		SMPSO	0.74	<0.001	0.37	<0.001	0.4	<0.001	0.1	<0.001
	AbYSS	RS	<0.01	<0.001	0.82	<0.001	0.53	<0.05	>0.99	<0.001
		CellIDE	<0.01	<0.001	0.56	<0.05	0.5	1	>0.99	<0.001
		GDE3	>0.99	<0.001	0.32	<0.001	0.5	1	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.16	<0.001	0.38	<0.001	<0.01	<0.001
	CellIDE	RS	<0.01	<0.001	0.56	<0.05	0.5	1	>0.99	<0.001
		GDE3	>0.99	<0.001	0.27	<0.001	0.5	1	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.13	<0.001	0.38	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	GDE3	SMPSO	0.97	<0.001	0.27	<0.001	0.38	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.73	<0.001	0.51	1	>0.99	<0.001
	SMPSO	RS	<0.01	<0.001	0.88	<0.001	0.63	<0.001	>0.99	<0.001
S4	NSGA-II	NSGA-III	0.65	<0.001	0.6	<0.05	0.53	0.42	0.49	0.52
		MoCell	<0.01	<0.001	<0.01	<0.001	0.73	<0.001	>0.99	<0.001
		SPEA2	0.97	<0.001	0.9	<0.001	0.45	0.24	0.05	<0.001
		AbYSS	<0.01	<0.001	<0.01	<0.001	0.71	<0.001	>0.99	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.77	<0.001	>0.99	<0.001
		GDE3	0.96	<0.001	0.9	<0.001	0.52	0.62	0.02	<0.001
		SMPSO	>0.99	<0.001	0.41	0.09	0.4	<0.001	0.04	<0.001
	NSGA-III	RS	<0.01	<0.001	<0.01	<0.001	0.78	<0.001	>0.99	<0.001
		MoCell	<0.01	<0.001	<0.01	<0.001	0.7	<0.001	>0.99	<0.001
		SPEA2	0.78	<0.001	0.74	<0.001	0.42	<0.05	0.06	<0.001
		AbYSS	<0.01	<0.001	0.01	<0.001	0.69	<0.001	>0.99	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.75	<0.001	>0.99	<0.001
		GDE3	0.74	<0.001	0.72	<0.001	0.49	0.72	0.03	<0.001
		SMPSO	0.96	<0.001	0.36	<0.001	0.37	<0.001	0.06	<0.001
	MoCell	RS	<0.01	<0.001	<0.01	<0.001	0.76	<0.001	>0.99	<0.001
		SPEA2	>0.99	<0.001	>0.99	<0.001	0.23	<0.001	<0.01	<0.001
		AbYSS	>0.99	<0.001	0.87	<0.001	0.49	0.59	0.03	<0.001
		CellIDE	0.22	<0.001	0.37	<0.05	0.56	<0.05	0.79	<0.001
		GDE3	>0.99	<0.001	>0.99	<0.001	0.3	<0.001	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.7	<0.001	0.22	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.57	<0.001	>0.99	<0.001
	SPEA2	AbYSS	<0.01	<0.001	<0.01	<0.001	0.76	<0.001	>0.99	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.81	<0.001	>0.99	<0.001
		GDE3	0.39	<0.05	0.45	0.29	0.57	0.11	0.54	0.36
		SMPSO	0.94	<0.001	0.23	<0.001	0.44	<0.05	0.55	0.46
	AbYSS	RS	<0.01	<0.001	<0.01	<0.001	0.82	<0.001	>0.99	<0.001
		CellIDE	<0.01	<0.001	0.08	<0.001	0.57	<0.05	>0.99	<0.001
		GDE3	>0.99	<0.001	>0.99	<0.001	0.31	<0.001	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.68	<0.001	0.23	<0.001	<0.01	<0.001
	CellIDE	RS	<0.01	<0.001	<0.01	<0.001	0.59	<0.001	>0.99	<0.001
		GDE3	>0.99	<0.001	>0.99	<0.001	0.25	<0.001	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.7	<0.001	0.18	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.52	0.15	>0.99	<0.001
	GDE3	SMPSO	0.96	<0.001	0.24	<0.001	0.38	<0.001	0.44	0.63

S5	SMP	RS	<0.01	<0.001	<0.01	<0.001	0.76	<0.001	>0.99	<0.001
		RS	<0.01	<0.001	0.3	<0.001	0.83	<0.001	>0.99	<0.001
	NSGA-II	NSGA-III	0.43	0.08	0.51	0.81	0.51	0.94	0.56	0.28
		MoCell	<0.01	<0.001	0.75	<0.001	0.75	<0.001	>0.99	<0.001
		SPEA2	0.96	<0.001	0.39	<0.05	0.39	<0.001	0.05	<0.001
		AbYSS	<0.01	<0.001	0.73	<0.001	0.73	<0.001	>0.99	<0.001
		CellIDE	<0.01	<0.001	0.73	<0.001	0.73	<0.001	>0.99	<0.001
		GDE3	0.8	<0.001	0.51	0.99	0.51	0.92	0.17	<0.001
		SMP	0.99	<0.001	0.28	<0.001	0.28	<0.001	<0.01	<0.001
	NSGA-III	RS	<0.01	<0.001	0.75	<0.001	0.75	<0.001	>0.99	<0.001
		MoCell	<0.01	<0.001	0.74	<0.001	0.74	<0.001	>0.99	<0.001
		SPEA2	0.97	<0.001	0.38	<0.001	0.38	<0.001	0.04	<0.001
		AbYSS	<0.01	<0.001	0.72	<0.001	0.72	<0.001	>0.99	<0.001
		CellIDE	<0.01	<0.001	0.72	<0.001	0.72	<0.001	>0.99	<0.001
		GDE3	0.87	<0.001	0.5	0.94	0.5	0.66	0.13	<0.001
		SMP	0.99	<0.001	0.27	<0.001	0.27	<0.001	<0.01	<0.001
	MoCell	RS	<0.01	<0.001	0.74	<0.001	0.74	<0.001	>0.99	<0.001
		SPEA2	>0.99	<0.001	0.18	<0.001	0.18	<0.001	<0.01	<0.001
		AbYSS	>0.99	<0.001	0.48	0.13	0.48	0.13	<0.01	<0.001
		CellIDE	0.68	<0.001	0.49	0.23	0.49	0.23	0.33	<0.001
		GDE3	>0.99	<0.001	0.27	<0.001	0.27	<0.001	<0.01	<0.001
		SMP	>0.99	<0.001	0.13	<0.001	0.13	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.51	1	0.51	1	>0.99	<0.001
	SPEA2	AbYSS	<0.01	<0.001	0.8	<0.001	0.8	<0.001	>0.99	<0.001
		CellIDE	<0.01	<0.001	0.81	<0.001	0.81	<0.001	>0.99	<0.001
		GDE3	0.12	<0.001	0.62	<0.05	0.62	<0.05	0.88	<0.001
		SMP	0.71	<0.001	0.38	<0.001	0.38	<0.001	0.24	<0.001
	AbYSS	RS	<0.01	<0.001	0.82	<0.001	0.82	<0.001	>0.99	<0.001
		CellIDE	<0.01	<0.001	0.51	0.78	0.51	0.78	>0.99	<0.001
		GDE3	>0.99	<0.001	0.29	<0.001	0.29	<0.001	<0.01	<0.001
		SMP	>0.99	<0.001	0.14	<0.001	0.14	<0.001	<0.01	<0.001
	CellIDE	RS	<0.01	<0.001	0.53	<0.05	0.53	<0.05	>0.99	<0.001
		GDE3	>0.99	<0.001	0.29	<0.001	0.29	<0.001	<0.01	<0.001
		SMP	>0.99	<0.001	0.14	<0.001	0.14	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.52	0.07	0.52	0.07	>0.99	<0.001
	GDE3	SMP	0.96	<0.001	0.28	<0.001	0.28	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.73	<0.001	0.73	<0.001	>0.99	<0.001
	SMP	RS	<0.01	<0.001	0.88	<0.001	0.88	<0.001	>0.99	<0.001

A.4.3 Results of Rank Values and Confidence Values

TABLE A-12 Rank values and confidence values for each objectives of each strategy (AW4)

Str	Algorithms	Rank Value				Confidence Value			
		PTM	O2 of Si	PTR	HV	PTM	O2 of Si	PTR	HV
S2	NSGA-II	2	5	1	4	8.0%	13.5%	4.5%	11.8%
	NSGA-III	2	6	3	4	8.0%	16.2%	13.6%	11.8%
	MoCell	1	4	3	2	4.0%	10.8%	13.6%	5.9%
	SPEA2	5	7	1	6	20.0%	18.9%	4.5%	17.6%
	AbYSS	3	3	2	3	12.0%	8.1%	9.1%	8.8%
	CellIDE	1	2	4	2	4.0%	5.4%	18.2%	5.9%
	GDE3	4	8	2	5	16.0%	21.6%	9.1%	14.7%
	SMP	6	1	2	7	24.0%	2.7%	9.1%	20.6%
S3	RS	1	1	4	1	4.0%	2.7%	18.2%	2.9%
	NSGA-II	4	3	3	4	12.1%	9.7%	12.5%	12.1%
	NSGA-III	4	3	3	4	12.1%	9.7%	12.5%	12.1%
	MoCell	1	5	3	1	3.0%	16.1%	12.5%	3.0%
	SPEA2	6	2	2	6	18.2%	6.5%	8.3%	18.2%
	AbYSS	3	4	3	3	9.1%	12.9%	12.5%	9.1%
	CellIDE	2	5	3	2	6.1%	16.1%	12.5%	6.1%
	GDE3	5	3	3	5	15.2%	9.7%	12.5%	15.2%
S4	SMP	7	1	1	7	21.2%	3.2%	4.2%	21.2%
	RS	1	5	3	1	3.0%	16.1%	12.5%	3.0%
	NSGA-II	4	4	2	4	10.8%	12.5%	8.7%	13.3%
	NSGA-III	5	5	2	4	13.5%	15.6%	8.7%	13.3%
	MoCell	2	2	3	2	5.4%	6.3%	13.0%	6.7%
	SPEA2	7	6	2	5	18.9%	18.8%	8.7%	16.7%
	AbYSS	3	3	3	3	8.1%	9.4%	13.0%	10.0%
	CellIDE	1	1	4	1	2.7%	3.1%	17.4%	3.3%
S5	GDE3	6	6	2	5	16.2%	18.8%	8.7%	16.7%
	SMP	8	4	1	5	21.6%	12.5%	4.3%	16.7%
	RS	1	1	4	1	2.7%	3.1%	17.4%	3.3%
	NSGA-II	4	3	3	4	12.1%	10.7%	10.7%	12.1%
	NSGA-III	4	3	3	4	12.1%	10.7%	10.7%	12.1%

	MoCell	1	4	4	1	3.0%	14.3%	14.3%	3.0%
	SPEA2	6	2	2	6	18.2%	7.1%	7.1%	18.2%
	AbYSS	3	4	4	3	9.1%	14.3%	14.3%	9.1%
	CellIDE	2	4	4	2	6.1%	14.3%	14.3%	6.1%
	GDE3	5	3	3	5	15.2%	10.7%	10.7%	15.2%
	SMPSO	7	1	1	7	21.2%	3.6%	3.6%	21.2%
	RS	1	4	4	1	3.0%	14.3%	14.3%	3.0%

A.5 GS

A.5.1 Kruskal–Wallis Test

TABLE A-13 Kruskal–Wallis Test for each objective of each strategy (GS1)

Str.	PTM		O2 of Si		PTR		HV	
	DF	Prob> ChiSq	DF	Prob> ChiSq	DF	Prob> ChiSq	DF	Prob> ChiSq
S2	8	<.0001	8	<.0001	8	<.0001	8	<.0001
S3	8	<.0001	8	<.0001	8	<.0001	8	<.0001
S4	8	<.0001	8	<.0001	8	<.0001	8	<.0001
S5	8	<.0001	8	<.0001	8	<.0001	8	<.0001

A.5.2 Mann-Whitney U Test and Vargha and Delaney statistics

TABLE A-14 Mann-Whitney U Test and Vargha and Delaney statistics for each objective of each strategy (GS1)

Str	Algorithm A	Algorithm B	PTM		O2 of Si		PTR		HV	
			A_{12}	p-value	A_{12}	p-value	A_{12}	p-value	A_{12}	p-value
S2	NSGA-II	NSGA-III	0.69	<0.001	0.74	<0.001	0.6	<0.05	0.31	<0.001
		MoCell	<0.01	<0.001	<0.01	<0.001	0.68	<0.001	>0.99	<0.001
		SPEA2	>0.99	<0.001	>0.99	<0.001	0.34	<0.001	<0.01	<0.001
		AbYSS	>0.99	<0.001	<0.01	<0.001	0.67	<0.001	<0.01	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.68	<0.001	>0.99	<0.001
		GDE3	<0.01	<0.001	<0.01	<0.001	0.5	0.8	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.05	<0.001	0.11	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.68	<0.001	>0.99	<0.001
	NSGA-III	MoCell	<0.01	<0.001	<0.01	<0.001	0.58	<0.001	>0.99	<0.001
		SPEA2	>0.99	<0.001	0.9	<0.001	0.26	<0.001	0.02	<0.001
		AbYSS	>0.99	<0.001	<0.01	<0.001	0.57	<0.05	<0.01	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.58	<0.001	>0.99	<0.001
		GDE3	<0.01	<0.001	<0.01	<0.001	0.4	<0.05	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.05	<0.001	0.08	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.58	<0.001	>0.99	<0.001
		MoCell	<0.01	<0.001	<0.01	<0.001	0.58	<0.001	>0.99	<0.001
	MoCell	SPEA2	>0.99	<0.001	>0.99	<0.001	0.19	<0.001	<0.01	<0.001
		AbYSS	>0.99	<0.001	0.09	<0.001	0.5	1	<0.01	<0.001
		CellIDE	0.24	<0.001	0.2	<0.001	0.5	1	0.63	<0.05
		GDE3	>0.99	<0.001	0.98	<0.001	0.33	<0.001	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.16	<0.001	0.06	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		SPEA2	>0.99	<0.001	<0.01	<0.001	0.8	<0.001	<0.01	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.81	<0.001	>0.99	<0.001
	SPEA2	GDE3	<0.01	<0.001	<0.01	<0.001	0.65	<0.001	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.05	<0.001	0.21	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.81	<0.001	>0.99	<0.001
		AbYSS	<0.01	<0.001	0.74	<0.001	0.51	1	>0.99	<0.001
		GDE3	<0.01	<0.001	>0.99	<0.001	0.34	<0.001	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.22	<0.001	0.06	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.51	1	>0.99	<0.001
		CellIDE	>0.99	<0.001	>0.99	<0.001	0.33	<0.001	<0.01	<0.001
	CellIDE	SMPSO	>0.99	<0.001	0.19	<0.001	0.06	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	>0.99	<0.001	0.06	<0.001	0.12	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.67	<0.001	>0.99	<0.001
		SMPSO	<0.01	<0.001	0.38	0.25	0.94	<0.001	>0.99	<0.001
	GDE3	SMPSO	>0.99	<0.001	0.06	<0.001	0.12	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.67	<0.001	>0.99	<0.001
		SMPSO	<0.01	<0.001	0.38	0.25	0.94	<0.001	>0.99	<0.001
		RS	<0.01	<0.001	0.38	0.25	0.94	<0.001	>0.99	<0.001
		SMPSO	<0.01	<0.001	0.38	0.25	0.94	<0.001	>0.99	<0.001
		RS	<0.01	<0.001	0.38	0.25	0.94	<0.001	>0.99	<0.001
		SMPSO	<0.01	<0.001	0.38	0.25	0.94	<0.001	>0.99	<0.001
		RS	<0.01	<0.001	0.38	0.25	0.94	<0.001	>0.99	<0.001
S3	NSGA-II	NSGA-III	0.68	<0.001	0.49	0.35	0.5	1	0.33	<0.001
		MoCell	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SPEA2	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		AbYSS	0.9	<0.001	0.5	1	0.5	1	0.1	<0.001
		CellIDE	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.07	<0.001	0.35	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	NSGA-III	MoCell	<0.01	<0.001	0.51	0.35	0.5	1	>0.99	<0.001
		SPEA2	>0.99	<0.001	0.51	0.77	0.5	1	0.01	<0.001
		AbYSS	0.77	<0.001	0.51	0.35	0.5	1	0.23	<0.001
		MoCell	<0.01	<0.001	0.51	0.35	0.5	1	>0.99	<0.001
		SPEA2	>0.99	<0.001	0.51	0.77	0.5	1	0.01	<0.001
		AbYSS	0.77	<0.001	0.51	0.35	0.5	1	0.23	<0.001
		MoCell	<0.01	<0.001	0.51	0.35	0.5	1	>0.99	<0.001
		SPEA2	>0.99	<0.001	0.51	0.77	0.5	1	0.01	<0.001
		AbYSS	0.77	<0.001	0.51	0.35	0.5	1	0.23	<0.001

		CellIDE	<0.01	<0.001	0.51	0.35	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.001	0.51	0.35	0.5	1	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.07	<0.001	0.35	<0.001	<0.01	<0.001
	MoCell	RS	<0.01	<0.001	0.51	0.35	0.5	1	>0.99	<0.001
		SPEA2	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		AbYSS	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		CellIDE	0.04	<0.001	0.5	1	0.5	1	0.96	<0.001
		GDE3	0.95	<0.001	0.5	1	0.5	1	0.05	<0.001
		SMPSO	>0.99	<0.001	0.07	<0.001	0.35	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	SPEA2	AbYSS	0.01	<0.001	0.51	1	0.5	1	0.98	<0.001
		CellIDE	<0.01	<0.001	0.51	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.001	0.51	1	0.5	1	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.07	<0.001	0.35	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.51	1	0.5	1	>0.99	<0.001
	AbYSS	CellIDE	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.07	<0.001	0.35	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	CellIDE	GDE3	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.07	<0.001	0.35	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	GDE3	SMPSO	>0.99	<0.001	0.07	<0.001	0.35	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	SMPSO	RS	<0.01	<0.001	0.93	<0.001	0.65	<0.001	>0.99	<0.001
S4	NSGA-II	NSGA-III	0.35	<0.001	0.32	<0.001	0.55	<0.05	0.45	0.33
		MoCell	<0.01	<0.001	<0.01	<0.001	0.55	<0.05	>0.99	<0.001
		SPEA2	>0.99	<0.001	>0.99	<0.001	0.46	0.12	<0.01	<0.001
		AbYSS	>0.99	<0.001	<0.01	<0.001	0.55	<0.05	0.74	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.55	<0.05	>0.99	<0.001
		GDE3	<0.01	<0.001	<0.01	<0.001	0.55	<0.05	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.41	0.89	0.13	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.55	<0.05	>0.99	<0.001
	NSGA-III	MoCell	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		SPEA2	>0.99	<0.001	>0.99	<0.001	0.41	<0.001	<0.01	<0.001
		AbYSS	>0.99	<0.001	0.02	<0.001	0.5	1	0.74	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.42	0.65	0.11	<0.001	<0.01	<0.001
	MoCell	RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		SPEA2	>0.99	<0.001	>0.99	<0.001	0.41	<0.001	<0.01	<0.001
		AbYSS	>0.99	<0.001	0.94	<0.001	0.5	1	<0.01	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	>0.99	<0.001	0.98	<0.001	0.5	1	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.58	<0.001	0.11	<0.001	<0.01	<0.001
	SPEA2	RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		AbYSS	0.11	<0.001	<0.01	<0.001	0.59	<0.001	>0.99	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.59	<0.001	>0.99	<0.001
		GDE3	<0.01	<0.001	<0.01	<0.001	0.59	<0.001	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.33	0.17	0.14	<0.001	<0.01	<0.001
	AbYSS	RS	<0.01	<0.001	<0.01	<0.001	0.59	<0.001	>0.99	<0.001
		CellIDE	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.001	0.35	<0.001	0.5	1	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.53	<0.05	0.11	<0.001	<0.01	<0.001
	CellIDE	RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		GDE3	>0.99	<0.001	>0.99	<0.001	0.5	1	<0.01	<0.001
		SMPSO	>0.99	<0.001	0.63	<0.001	0.11	<0.001	<0.01	<0.001
	GDE3	RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.57	<0.05	0.11	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	<0.01	<0.001	0.5	1	>0.99	<0.001
	SMPSO	RS	<0.01	<0.001	0.28	<0.001	0.89	<0.001	>0.99	<0.001
S5	NSGA-II	NSGA-III	0.58	0.09	0.5	1	0.5	1	0.42	0.08
		MoCell	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SPEA2	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		AbYSS	0.84	<0.001	0.5	1	0.5	1	0.16	<0.001
		CellIDE	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.35	<0.001	0.08	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	NSGA-III	MoCell	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SPEA2	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		AbYSS	0.77	<0.001	0.5	1	0.5	1	0.23	<0.001
		CellIDE	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SMPSO	>0.99	<0.001	0.35	<0.001	0.08	<0.001	<0.01	<0.001
	MoCell	RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SPEA2	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001

		AbYSS	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		CellIDE	0.04	<0.001	0.5	1	0.5	1	0.96	<0.001
		GDE3	0.94	<0.001	0.5	1	0.5	1	0.06	<0.001
		SMP SO	>0.99	<0.001	0.35	<0.001	0.08	<0.001	<0.01	<0.001
	SPEA2	RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		AbYSS	<0.01	<0.001	0.5	1	0.51	1	>0.99	<0.001
		CellIDE	<0.01	<0.001	0.5	1	0.51	1	>0.99	<0.001
		GDE3	<0.01	<0.001	0.5	1	0.51	1	>0.99	<0.001
	AbYSS	SMP SO	>0.99	<0.001	0.35	<0.001	0.08	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.51	1	>0.99	<0.001
		CellIDE	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		GDE3	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
	CellIDE	SMP SO	>0.99	<0.001	0.35	<0.001	0.08	<0.001	<0.01	<0.001
		RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		GDE3	>0.99	<0.001	0.5	1	0.5	1	<0.01	<0.001
		SMP SO	>0.99	<0.001	0.35	<0.001	0.08	<0.001	<0.01	<0.001
	GDE3	RS	<0.01	<0.001	0.5	1	0.5	1	>0.99	<0.001
		SMP SO	>0.99	<0.001	0.35	<0.001	0.08	<0.001	<0.01	<0.001
	SMP SO	RS	<0.01	<0.001	0.65	<0.001	0.93	<0.001	>0.99	<0.001

A.5.3 Results of Rank Values and Confidence Values

TABLE A-15 Rank values and confidence values for each objectives of each strategy (GS1)

Str	Algorithms	Rank Value				Confidence Value			
		PTM	O2 of Si	PTR	HV	PTM	O2 of Si	PTR	HV
S2	NSGA-II	4	5	3	5	10.8%	16.7%	9.1%	11.1%
	NSGA-III	5	6	4	6	13.5%	20.0%	12.1%	13.3%
	MoCell	2	3	5	3	5.4%	10.0%	15.2%	6.7%
	SPEA2	6	7	2	7	16.2%	23.3%	6.1%	15.6%
	AbYSS	7	1	5	8	18.9%	3.3%	15.2%	17.8%
	CellIDE	1	2	5	2	2.7%	6.7%	15.2%	4.4%
	GDE3	3	4	3	4	8.1%	13.3%	9.1%	8.9%
	SMP SO	8	1	1	9	21.6%	3.3%	3.0%	20.0%
S3	RS	1	1	5	1	2.7%	3.3%	15.2%	2.2%
	NSGA-II	4	2	2	4	10.8%	11.8%	11.8%	10.8%
	NSGA-III	5	2	2	5	13.5%	11.8%	11.8%	13.5%
	MoCell	2	2	2	2	5.4%	11.8%	11.8%	5.4%
	SPEA2	7	2	2	7	18.9%	11.8%	11.8%	18.9%
	AbYSS	6	2	2	6	16.2%	11.8%	11.8%	16.2%
	CellIDE	1	2	2	1	2.7%	11.8%	11.8%	2.7%
	GDE3	3	2	2	3	8.1%	11.8%	11.8%	8.1%
S4	SMP SO	8	1	1	8	21.6%	5.9%	5.9%	21.6%
	RS	1	2	2	1	2.7%	11.8%	11.8%	2.7%
	NSGA-II	5	6	2	5	13.5%	17.6%	8.7%	14.7%
	NSGA-III	4	5	3	5	10.8%	14.7%	13.0%	14.7%
	MoCell	2	2	3	2	5.4%	5.9%	13.0%	5.9%
	SPEA2	7	7	2	6	18.9%	20.6%	8.7%	17.6%
	AbYSS	6	4	3	4	16.2%	11.8%	13.0%	11.8%
	CellIDE	1	1	3	1	2.7%	2.9%	13.0%	2.9%
S5	GDE3	3	3	3	3	8.1%	8.8%	13.0%	8.8%
	SMP SO	8	5	1	7	21.6%	14.7%	4.3%	20.6%
	RS	1	1	3	1	2.7%	2.9%	13.0%	2.9%
	NSGA-II	4	2	2	4	12.1%	11.8%	11.8%	12.1%
	NSGA-III	4	2	2	4	12.1%	11.8%	11.8%	12.1%
	MoCell	2	2	2	2	6.1%	11.8%	11.8%	6.1%
	SPEA2	6	2	2	6	18.2%	11.8%	11.8%	18.2%
	AbYSS	5	2	2	5	15.2%	11.8%	11.8%	15.2%
	CellIDE	1	2	2	1	3.0%	11.8%	11.8%	3.0%
	GDE3	3	2	2	3	9.1%	11.8%	11.8%	9.1%
	SMP SO	7	1	1	7	21.2%	5.9%	5.9%	21.2%
	RS	1	2	2	1	3.0%	11.8%	11.8%	3.0%