

# Combinatorial Methods for Enhancing the Resilience of Production Facilities

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**Abstract**—In this paper, we apply combinatorial methods to generate crisis scenarios for production facilities with the goal of strengthening their resilience by identifying weaknesses in operational aspects or crisis response plans, extending previous work from the domain of disaster research. We use notions of combinatorial coverage for quantifying diversity in scenarios and as one objective when sampling the considered scenario space.

**Index Terms**—combinatorial testing, resilience, production industry, planspiele, crisis exercises.

## I. INTRODUCTION

The Coronavirus disease (COVID-19) pandemic has caused many significant changes in the lives of millions and humankind globally, impacting nearly every aspect of our lives and causing significant health threats. It has also shaken the production industry and global supply chains at their core, revealing that global supply chains are much more vulnerable than anticipated [1]. This recognition has to be incorporated into *business continuity management* (BCM) and *business impact analysis* (BIA). Crisis exercises (also called *planspiele*) are an important part of (crisis) preparedness and should be conducted on a regular basis. In this paper, following the approach proposed in [2], we use combinatorial methods to generate *crisis scenarios* for use in crisis preparedness efforts, taking as example a hypothetical production facility near a medium-sized European city and targeting both BIA and BCM aspects. In particular, we use *t*-way test sets (derived from covering arrays (CAs)) as well as sequence test sets (derived from sequence covering arrays (SCAs) and combinatorial sequence structures with constraints) to generate crisis scenarios and exercises which provide guaranteed diversity in terms of combinatorial (tuple- or sequence-) coverage, while

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at the same time being optimized for small size with the underlying motivation that the combinatorial properties of the generated crisis scenarios provide a structured way to uncover weaknesses or shortcoming in crisis response plans or impact assessments with the goal to increase the overall resilience of a production facility.

**Contribution.** In particular, this paper makes the following contributions:

- Proposes the use of *t*-way test sets for modelling issues in production chains;
- Instantiates the scenario generation approach proposed in [2] for crises exercises for a production facility;
- Discusses practical issues for descriptive crisis scenario generation for crisis exercises for the production industry.

*This paper is structured as follows.* In Section II, we discuss related work. We briefly provide some preliminaries for this work in Section III. We detail the application of combinatorial methods for crisis scenario generation for a production facility in Section IV. In Section VI, we conclude and also provide an outlook on future work.

## II. RELATED WORK

How to plan for, prepare against and aim to recover from disruptive events and incidents has been codified in international standardization documents [3] with a recent amendment pointing out to also take potential impact of climate change into account [4]. Guidelines for conducting exercises have been published from a military perspective [5], but also codified in a standard [6] for societal security. In [2], the authors propose the use of combinatorial sequences for disaster scenario generation. Recent technological advances have led to some training exercises to be conducted in augmented reality environments [7].

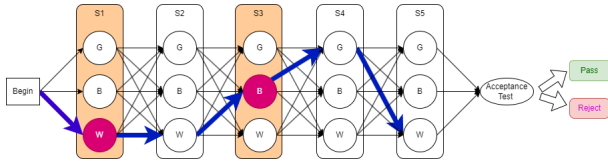


Fig. 1. Production chain with steps  $S1$  to  $S5$ , each having exactly one of the outcomes of  $g$ ,  $b$  or  $w$ . Highlighted is a pairwise step-outcome value-selection that is covered by the blue path.

### III. PRELIMINARIES

In this section, we provide a succinct overview of the concepts and underlying mathematical structures that we use in this work and point to [8] for an in-depth treatment.  $t$ -way test sets provide guaranteed coverage for variable-value interactions with oftentimes significantly lower number of test cases compared to the cardinality of the full input space given by the Cartesian product of parameter value sets. A corresponding notion of sequential coverage has been given in [9] and extended to more general types of sequences than permutations also featuring constraints in [10].

### IV. COMBINATORIAL METHODS FOR PRODUCTION FACILITY RESILIENCE

In this section, we model interactions of sources of risk combinatorially for a hypothetical production facility and also generate corresponding *scenarios*<sup>1</sup> as means to assess the resilience of the operations of this facility. We first consider internal production issues in Section IV-A and second stress- or crisis scenarios for the overall operations of the facility in Section IV-B.

#### A. Combinatorial Modelling for Production Chain Issues

We assume a production chain of  $N$  steps, which constitutes the highest level of the production view and which outputs the main final products, which are then passed on to customers. These end products, which have passed all  $N$  production steps, will then undergo acceptance testing at the end, the result of which is provided by what we call an *acceptance oracle*. This situation is visualized in Figure 1. Whether every object will be tested individually or a sampling strategy employed, depends on the specific requirements and circumstances of the production facility. We consider now the following question in context: What kind of errors/defects caused by different combinations of individual production step quality issues can be detected by the acceptance oracle? For example, some issues may only manifest themselves after certain amount of usage or expose time before they cause operational failures in the produced objects, caused by wear and tear.

To devise a discretized model for such production chains, consider that each step can result in one and only one of the possible outcomes: good ( $g$ ), worse ( $w$ ) or bad ( $b$ ). These

<sup>1</sup>All  $t$ -way test sets were generated using the web version of CAgEn [11] and all sequence scenario sets using research prototype implementations; with all computations carried out on consumer grade laptops in running times under one minute.

outcomes are also depicted in Figure 1 for the steps  $S1$  to  $S5$ . Every object that is produced by this chain has passed through all steps exactly once, however, we further assume that we don't know the specific individual outcome of each step. We further assume that different outcomes in each step will have different impact on detectability by the acceptance oracle. Overall, there are  $3^N$  possible paths through this chain. Since the order of the production steps is fixed and under the additional assumption that the individual steps are independent of each other, we map each production step to a parameter in an IPM taking ternary values  $g$ ,  $b$  or  $w$ . Then, all possible paths through this chain correspond to an exhaustive test set generated by this IPM. In order to design and evaluate fine-grained acceptance oracles, which consider as many different production step outcomes as possible while simultaneously aiming to minimize their number, we propose the use of combinatorial test sets.

To continue with the concrete example of the production chain depicted in Figure 1 consisting of five steps with each one taking one of three outcomes, a pairwise test set with 15 tests can be constructed. Higher-strength test sets, having 45 for 3-way and 81 for 4-way coverage tests, can also be constructed. Note, that this corresponds to a reduction of around 93, 81 and 66 percent for 2-way to 4-way test sets, respectively, compared to the exhaustive input space of  $243 (= 3^5)$ . These combinatorially generated test sets encode paths through the production chain and the combinatorial coverage translated for pairwise coverage now means that for any possible outcome value pair (i.e.,  $ww$ ,  $gg$ ,  $bb$ ,  $wg$ ,  $bg$ ,  $gw$ ,  $gb$ ,  $wb$ ,  $bw$ ) for any possible unordered selection of two different steps (i.e.,  $S1S2$ ,  $S1S3$ ,  $S1S4$ ,  $S1S5$ ,  $S2S3$ ,  $S2S4$ ,  $S2S5$ ,  $S3S4$ ,  $S3S5$ ,  $S4S5$ ) there arises at least one path from one test in the generated pairwise test set that will go for the two selected steps through the two selected outcome-values. The corresponding case for pairwise coverage of a path passing through the selected steps  $S1$  and  $S3$  and the selected outcome-values  $w$  and  $b$ , respectively, is shown with blue arrows in Figure 1.

Every combinatorially generated path through the production chain can now be used to create or evaluate whether the acceptance oracle can detect the specific issue encoded in it or not. By using constraints in the IPM, it is also possible to exclude tuples (of arbitrary size) that are not of interest (potentially like the quintuple  $(g,g,g,g,g)$  in our example).

We would like to point out, that the proposed CT-based node coverage of the corresponding directed graph (as visualized in Figure 1) can also be seen as a special kind of graph coverage property. Furthermore, CAs provide a constructive minimized solution to the considered coverage problem.

#### B. Combinatorial Planspiele for a Production Facility

We model threats to a production facility coming from three origins: supplier side, production facility itself and customer side. All threats arising from these three origins have aspects and can manifest in both the physical- as well as the cyber-domain. Crisis exercises target to evaluate the resilience of

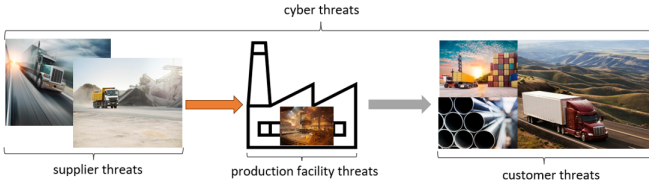


Fig. 2. Different threats to the facility.

response plans (assuming they exist in the first place). In particular, for the considered production facility, response plans have to guarantee production will continue under *all threat-scenarios* to avoid a costly production stop. This situation visualized in Figure 2. For every one of the three given origins of threats above, we list below a few specific threats:

- Supplier side:
  - Delays due to road blockings.
- Production facility:
  - Staff unavailability.
  - Cyber attack renders IT infrastructure unavailable.
- Customer side:
  - News article about defects in downstream product.
  - Important customer goes out of business.
  - New regulations require changes in production facility to stay compliant.

Following a descriptive crisis (or stress-) scenario generation approach based on [2], we show how combinatorial sequence testing methods can be used to obtain size-minimized sets of such scenarios that exhibit coverage of certain (sub-) sequences, including sub-permutations. To this end, we reformulate threats as events that can appear within the timeline of a crisis, which - for our running example of a production facility - leads to 12 crisis events in total (including the ones derived from the threats mentioned above).

We begin by utilizing SCAs and choose as event symbols all 12 events; then, pairwise sequential coverage can be achieved by an SCA of two scenarios. For coverage of higher-order subpermutations, an SCA of strength three with 23 (crisis) scenarios can be constructed, which provides a reduction of more than 99 percent compared to the size of the full permutation group of twelve elements.

Crisis scenarios derived from SCAs inherit the strictness of the underlying permutation model, meaning that in every such scenario every event will appear exactly once. A possible extension of this restrictive model has been proposed in [10] for combinatorial sequence testing with constraints, where the authors consider more general types of sequences while still maintaining the goal of covering prescribed sub-sequences called *t-way target sequences*. In particular, the approach in [10] can still enforce the coverage of *t-way* sub-permutations as part of *t-way* target sequences. To obtain crisis scenarios for the considered production facility via combinatorial sequence testing with constraints, we choose the following constraints (among others):

TABLE I  
DIFFERENT COMBINATORIAL SCENARIO SETS FOR 2-WAY TARGET SEQUENCES OF LENGTH SIX AND SEVEN WITH CONSTRAINTS.

Properties	$S_1$	$S_2$	$S_3$	$S_4$
Max. event repetition	1	1	2	2
Scenario length	6	7	6	7
Num. of cov. 2-way target seqs.	131	131	141	141
Num. of gen. scenarios	20	16	20	17
Generation time (in sec)	1.15	6.09	1.87	22.11

TABLE II  
EXCERPT OF GENERATED CRISIS SEQUENCES WITH CONSTRAINTS OF LENGTH 6.

Roadblock	Abs_empl	Roadblock	Abs_empl	Filled_WH	Partner_stock
Abs_empl	SW_Failure	Cust_A_rep	Publ_transp	Cust_B_rep	New_Reg
Filled_WH	New_Reg	Roadblock	Abs_empl	Cust_B_rep	Cyber_DDOS
SW_Failure	Roadblock	Abs_empl	Protests	Filled_WH	Publ_transp
Partner_stock	New_Reg	Protests	New_Reg	Cyber_DDOS	Filled_WH

- At least one of three *serious events* has to appear in every sequence: this constraint ensures that all generated sequences will have sufficient impact.
- Sequence length has to be six or seven: This constraint ensures that resources are preserved when using the generated sequences in actual crises exercises.
- Maximum repetition per event per sequence is two: This constraint enables more general sequences than permutations.

We generated four sets of crisis scenarios which aim for maximizing 2-way target sequence coverage utilizing the tool introduced in [10] for all 12 events together with constraints, featuring different combinations for the parameters regarding scenario length and maximum event repetition and give some of their properties in Table I. As can be observed, for these particular sets of constraints, allowing for longer scenarios reduces the number of scenarios that have to be generated to cover the same number of 2-way target sequences. An excerpt of generated crisis scenarios for pairwise target-sequences of length six is shown in Table II.

All of these generated sets of scenarios can be used to obtain individual crises scenarios that can be played within exercises. By construction, these generated sets of crisis scenarios aim for maximizing *sequential diversity* (in terms of *t-way* sub-permutations or *t-way* target sequences) while also being optimized for small size. The combinatorial properties provide a way to integrate structured (sequential) diversity into the exercise planning in order to test the resilience of response plans against different threat orderings. As a consequence, depending on goals, practicability or time availability, scenario designers have the choice to either conduct fewer, but more extensive exercises (for example, annual exercises taking up two full days) or shorter, more compact exercises that are conducted at a higher frequency (for example, 2 hour exercises which are conducted every 2 weeks). In progressing through more and more conducted combinatorially generated crisis exercises, more and more different sequential threat orderings will challenge the response- or crisis plans, thereby structurally evaluating the resilience of overall crisis preparedness efforts.

## V. REFLECTION AND PRACTICAL FEEDBACK

In this section, we offer a critical reflection on automated crisis scenario generation approaches and on potentially arising issues for their practical application.

In terms of threats encoded in events that will form crisis scenarios, feedback from a production company<sup>2</sup> stresses the importance of cyber threats, not only for attacks but also for compliance with regard to legislations such as NIS and NIS-2 in the European Union. In this regard, the approach presented in this work provides the means to generate crisis scenarios that feature events encoding different types of cyber threats.

In general, from practical experience and perspective, the length of scenarios that are presented in crisis exercises (i.e., planspiele) to participants should be around ten events. Even though some companies have crisis exercises planned annually, there are others that have lower frequencies such as only once every five years. Resources for each occurrence of such exercises are also often limited, in particular in the number of hours (or days) that are allocated for one exercise. This means that the number of different scenarios that can be played is limited and restricted to a few in the best case. The desired degree of coverage can be chosen freely in the generation step, but has implications on the number of generated scenarios, while also highlighting the optimization aspect of the considered combinatorial structures in this work. Hence, even more emphasis should be placed on precisely choosing those sequences that will be actually played. To reflect this already as part of the generation step, in extension of what has been proposed in this work, one should focus on the question of which (sub-) set of generated scenarios to select for actual execution during exercises, since it is clear that playing all possible scenarios - where their total number can go into the hundreds or more as mentioned in Section IV-B before - is clearly not feasible. Integrating constraints or weights into the modelling and generation process could also support the prioritization of scenarios.

Increased processing power together with digital twins could offer a way to execute and evaluate more scenarios for crisis or impact analysis, for example in connection with logistics [12]. However, even if operations and planning activities are supported by information technology, any humans involved will still require dedicated training in the form of crisis exercises, which even when performed (partly) with modern technology such as augmented or virtual reality, will - as of this writing - still be executed *only* at the processing speed of the human mind.

## VI. CONCLUSION & FUTURE WORK

In order to safeguard the operations of a production facility, preparation efforts to be able to properly handle various kinds of threats and disruptions are indispensable. In order to provide diverse crisis scenarios for preparation efforts, including exercises, we proposed the use of combinatorial methods and

notions of combinatorial coverage. For the discussed running example of a production facility located near a medium European city, we have also presented generated scenarios that take into account cyber- as well as non-cyber threats.

As part of future work, we will extend our presented modelling approach on using combinatorial methods as a structured means to find weaknesses in crisis preparation and response plans for increasing the resilience of the production industry. Particular attention will be given on how to integrate practical (resource) limitations and concerns already in the scenario modelling and generation process.

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**Disclaimer:** Certain software products are identified in this document. Such identification does not imply recommendation by the NIST, nor does it imply that the products identified are necessarily the best available for the purpose.

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<sup>2</sup>Due to confidentiality requirements, this Austrian production company is not further specified.