


DODGE: Ontology-Aware Risk Assessment via Object-Oriented Disruption Graphs[★]

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Abstract When considering risky events or actions, we must not downplay the role of involved objects: a charged battery in our phone averts the risk of being stranded in the desert after a flat tyre, and a functional firewall mitigates the risk of a hacker intruding the network. The *Common Ontology of Value and Risk* (COVER) highlights how the role of objects and their relationships remains pivotal to performing transparent, complete and accountable risk assessment. In this paper, we operationalize some of the notions proposed by COVER – such as *parthood* between objects and *participation* of objects in events/actions – by presenting a new framework for risk assessment: DODGE. DODGE enriches the expressivity of vetted formal models for risk – i.e., *fault trees* and *attack trees* – by bridging the disciplines of *ontology* and *formal methods* into an ontology-aware formal framework composed by a more expressive modelling formalism, *Object-Oriented Disruption Graphs* (ODGs), logic (ODGLog) and an intermediate query language (ODGLang). With these, DODGE allows risk assessors to pose questions about *disruption propagation*, *disruption likelihood* and *risk levels*, keeping the fundamental role of objects at risk always in sight.

Keywords: ontology, logic, risk, COVER, fault trees, attack trees

1 Introduction

Risk assessment is a key activity to identify, analyze and prioritize the risk in a system, and come up with (cost-)effective countermeasures [37]. This is true when considering *safety* (i.e., the absence of risk connected with unintentional malfunctions) and *security* (i.e., the absence of risk linked with intentional attacks) [34]. To perform transparent, complete and accountable risk assessment, it is fundamental to explicitly account for the role objects play in *Events* and *Actions* in which they participate, and for how their status affects safety and security interplay: a door being locked causes the impossible escape event in case of fire but simultaneously stops the action of a burglar entering your house

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[22, 26, 35]. Formalisms widely employed in industry and academia to conduct risk assessment – such as *fault trees* [30] and *attack trees* [33] – are not equipped to explicitly reason about objects. Without an explicit representation of objects at risk, it is impossible to evaluate their role in risk scenarios and to correctly evaluate the overall risk imposed on these objects: e.g., what is the risk level my car is subject to, considering that both its tyres can break (safety-related event) and its onboard computer can be hacked (security-related action)?

Objective. Provide an ontology-grounded formal approach for object-based risk representation and reasoning by combining and extending standard formalisms for safety (*fault trees*) and security (*attack trees*).

DODGE: bridging ontology and formal methods. To address this lack of expressivity, two promising fields must be taken into account: *ontologies for risk* and *model-based risk assessment*. On the one hand, risk ontologies – like the *Common Ontology of Value and Risk* (COVER) [32] – excel in providing a structured ground for reasoning about a specific domain of knowledge, transparently and explicitly laying out key concepts and relationships needed to reason about risk. While excellent for conceptualization and transparency, ontologies are however not designed to enable quantitative and applied risk evaluations. On the other hand, specific model-based technologies from the field of formal methods – like *fault trees* (FTs) and *attack trees* (ATs) – excel in providing applicable, tried and tested instruments for rigorous and quantitative risk assessment. These methods, however, sometimes rely on opaque conceptual assumptions and, in particular, do not offer the expressivity needed to explicitly reason about objects at risk. With DODGE we propose a risk assessment framework that enriches and extends the expressivity of vetted model-based technologies – such as FTs and ATs – while grounding them in the conceptual clarity of COVER. The result is a transparent and functional framework, composed by a more expressive model, *Object-oriented Disruption Graphs* (ODGs), a new logic, ODGLog, and an intermediate query language, ODGLang. With these components, DODGE allows risk assessors to pose questions about *disruption propagation*, *disruption likelihood* and *risk levels*[†], keeping the paramount role of objects at risk always in sight.

Object-oriented Disruption Graphs. Fundamental elements highlighted by the COVER ontological framework [32] – such as the *participation* of a given object in a risk-related *action/event* or the *parthood* relationship between different objects – are not expressible in classical risk assessment formalisms, such as FTs and ATs. We address this gap and operationalize these concepts by presenting *Object-oriented Disruption Graphs* (ODGs), a new formalism that extends the strengths of classical FT- and AT-based risk analysis accounting for the role of objects at risk (OaRs) in *disruption propagation*, *likelihood* and *risk calculation*.

ODGLog and ODGLang. To perform transparent decision-making w.r.t. safety and security of systems, practitioners need the ability to analyse their models in

[†]We adopt these notions from previous work. For a more in-depth discussion on the nuances of notions like *risk*, *disruption* and *propagation*, including their relation to the notion of *risk propagation*, see [10, 34].

a meaningful and thorough way. To cater for this need, we present ODGLog – a logic to formally query ODGs– and ODGLang, an intermediate domain-specific language to ease the querying process. With ODGLog and ODGLang practitioners can query ODGs to learn meaningful information about systems *disruptions* and *risk levels*. One could ask, for example: 1. Given that one of my tyres breaks, is my entire field trip compromised? 2. Is the probability of an attacker compromising the network larger/smaller than p ? 3. Given an object at risk (e.g., my laptop), what is the most risky security Action/safety Event in which it participates? 4. What is the maximum risk level imposed on my laptop, given all the Actions/Events in which it participates? We showcase property specification in ODGLog and ODGLang on an *ODG* model for a small but well-known and representative example from safety-security literature, modelling safety and security risks on a household given the status of a door lock [22, 26, 35].

Related work. This paper directly relates to approaches that seek to combine ATs and FTs and increase their expressive capabilities. In this sense, numerous works attempt combinations of FTs and ATs into joint safety-security models: these are collected in a recent survey on model-based formalisms for safety-security risk assessment [26]. Of the 14 selected formalisms in [26], 7 combine or extend FTs and ATs: Attack-Fault Trees [2], Component Fault Trees [21], Extended Fault Trees – also known as Fault Trees with Attacks [9], Boolean driven Markov processes (BDMPs) [4], Attack Tree Bow Ties [1], Failure-Attack-Countermeasure Graphs [31], and State/Event Fault Trees (SEFTs) [28]. Of these formalisms, only BDMPs and SEFTs explicitly integrate properties of objects by joining FTs and Petri nets, expressing that certain disruptions can only happen in certain states. However, both BDMPs and SEFTs do not explicitly address how 1. the *parthood* relation between objects and 2. the *participation* relation between objects and events/actions can influence the propagation of disruptions and the computations of risk levels. Furthermore, they do not allow for aggregation of risk levels on a given object, nor do they allow to compute an optimal configuration of states to minimize risk. Lastly, [19] presents Object-Oriented Fault Trees (OFTs), where each FT node is described by an object with instance variables containing information such as the node’s parents, children and type. Despite the name, OFTs do not account for objects participating in different events represented by FT nodes, nor can they account for risk aggregation on objects, given safety- and security-related events/actions.

Summary of contributions:

- 1) We operationalize concepts from COVER – such as objects *parthood* and *participation* in events/actions – via a more expressive model integrating FTs and ATs – Object-oriented Disruption Graphs (ODGs).
- 2) We develop ODGLog, a logic for ODGs that enables the creation of object-oriented queries about disruption propagation, likelihood and risk.
- 3) To ease usability, we provide ODGLang – a query language for ODGLog.
- 4) We showcase property specification via both ODGLog and ODGLang on the famous locked door example from literature [22, 26, 35].

2 Baseline Research

Fault and attack trees. FTs and ATs constitute a sensible starting point as they are popular technologies that already encode key concepts highlighted in the *Common Ontology of Value and Risk* (COVER) – such as *Events* and *Actions* – and pose a solid ground for model-based risk assessment. Fault tree analysis (FTA) [30] is a widespread technique to support safety risk assessment,

and the use of fault trees is required, e.g., by the Federal Aviation Administration, the Nuclear Regulatory Commission, in the ISO 26262 standard [16] for autonomous driving and for software development in aerospace systems. A *fault tree* (FT) (see Fig. 1, right) models *Events* that describe how component failures arise, and propagate disruption through the system, eventually leading to system-level failures. Leaves in a FT represent *basic events* (BEs), i.e. elements of the tree that do not need further refinement. Once these fail, the failure is propagated through the *intermediate events* (IEs) via *gates*, to eventually reach the *top level event* (TLE), which symbolizes system failure. When considering model-based risk assessment of systems security – *attack trees* (ATs) are widely employed.

ATs (see Fig. 1, left) are hierarchical diagrams that represent malicious *Actions* that can lead to a system being compromised [33, 23]. ATs are referred to by many system engineering frameworks, e.g. *UMLsec* [20] and *SysMLsec* [29], and are supported by industrial tools such as Isograph’s *AttackTree* [18]. The TLE of an AT represents the attacker compromising the entire system, and the leaves represent *basic attack steps* (BASes): actions of the attacker that can no longer be refined. As for FTs, intermediate nodes in ATs are labelled with gates.

COVER. The *Common Ontology of Value and Risk* (COVER) [32] is based on *UFO* [15] – a foundational ontology. It embeds a domain-independent conceptualization of risk, has been subject to validation and proper comparison to the literature of risk in risk analysis and management at large (e.g. [17]), and it is built upon widespread definitions of risk. This ontology has already shown its utility in constructing formalisms for risk quantification and propagation [10], and embeds several key assumptions about the nature of risk, which align with those in the literature in risk assessment. Firstly, the risk is **experiential**. This means that the notions of “event” and “object” are deeply entangled and, when assessing the risk an object is exposed to, one aggregates risks ascribed to events that can impact the object. For instance, consider the risks your laptop is exposed to. To assess them, you will need to consider:

1. which of your goals depend on your laptop (e.g. work deliverables);
2. what can happen to your laptop such that it would hinder its capability to achieve your goals (e.g. its screen breaking);

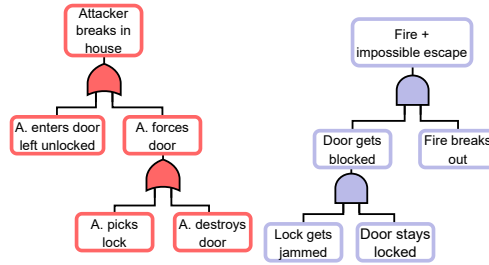


Figure 1: An attack tree (left) and a fault tree (right) for the locked door example.

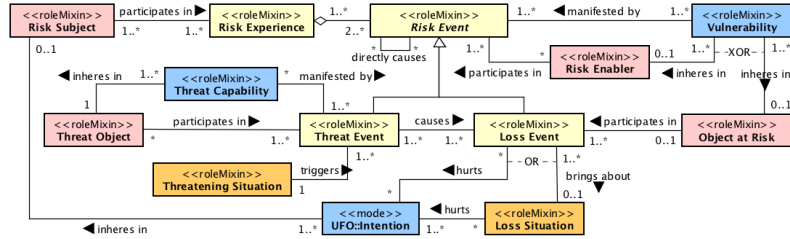


Figure 2: (COVER) Risk experience view [32].

3. which other events could cause these (e.g. you dropping it on the floor).

Then the risk your laptop (object) is exposed to is the aggregation of the risk of it falling (event) and breaking (event), and so on. The second assumption is that risk is **contextual**. Thus, the magnitude of the risk an object is exposed to may vary even if all its intrinsic properties (e.g., vulnerabilities or states) stay the same. To exemplify, let us pick one risk event involving your house door, namely that of robbers breaking into it. Naturally, the properties of the door – such as having a strengthened blocking mechanism – influence the magnitude of this risk. Still, the tools used by the robbers can significantly increase how risky the breaking event is. Lastly, another assumption that we derive from COVER is that risk is grounded on **uncertainty** about events and their outcomes. This is a very standard position – see [17] and [3] – which implies that likelihood is positively correlated with how risky an event is. For instance, the risk of encountering a bear is higher while walking in a forest than in an urban park, simply because it is more likely in the former case. Fig. 2 presents a perspective of COVER focused on the experiential aspect of risk (the diagram is represented in the OntoUML language [13]). It presents RISK EXPERIENCE as a multifaceted hypothetical occurrence that can be broken down into RISK EVENTS, further categorized into THREAT EVENTS and LOSS EVENTS. THREAT EVENTS are hypothetical occurrences capable of precipitating LOSS EVENTS, which, in turn, are incidents that undermine the objectives of a RISK SUBJECT, the AGENT whose viewpoint is under scrutiny in the risk evaluation process. A LOSS EVENT might involve OBJECTS AT RISK and RISK ENABLERS. Dispositions of objects at risk and risk enablers that can be manifested as threat and loss events are VULNERABILITIES. As discussed in [32] COVER accounts also for a numerical evaluation of RISK linked to a RISK ASSESSMENT. We emphasise here that the quantification of *risk* is applicable solely to *anticipated scenarios* that have the potential (though not certainty) to materialize. The ontology tackles this concern by acknowledging the feasibility of anticipated events, as discussed in [11].

Grounding DODGE in COVER. Throughout the paper, we highlight design assumptions used in the construction of both the new proposed model (ODGs) and logic (ODGLog) with the **assumption** tag. When presenting them, we discuss how they relate to – and are grounded in – the COVER ontology.

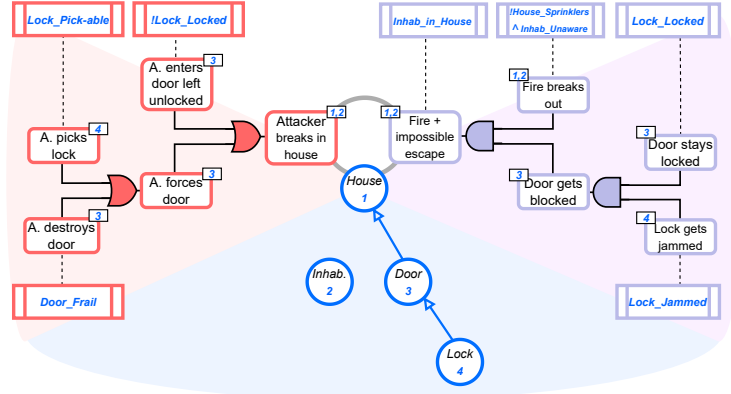


Figure 3: ODG for the locked door example.

3 Object-oriented Disruption Graphs

Object-oriented Disruption Graphs (ODGs) extend classical FT- and AT-based risk analysis by integrating key concepts from COVER, i.e., adding needed constructs to reason about objects at risk during risk assessment. Fig. 3 represents an Object-Oriented Disruption Graph for the locked door example [22, 26, 35]. On the left – in **red** – *Actions* of an attacker are represented in an AT. On the right – in **violet** – *Events* that can cause failures are represented in a FT. Root nodes in both the FT and AT – the *top level events* (TLEs) – can be mapped to COVER’s *Loss Events*. Each of the events/actions in the FT and AT is labelled with *objects at risk* (OaRs) that can *participate* in it – a white rectangle on the corner, with blue numbers. These numbers refer to the *Object Graph* – at the bottom, in **blue** – where arrows represent the *parthood* relationship. Specific combinations of properties of OaRs that are needed for events/actions to happen – what we call *conditions* – are typeset in blue and linked to FT/AT nodes via a dashed line. For example, the condition $\neg\text{Lock_Locked}$ is needed for the action *Attacker enters door left unlocked* to happen. With this model, one can ask ontology-aware questions that do not overlook the role of objects at risk, e.g., 1. Given that an *Attacker destroys the door* and that the *Fire does not break out*, are any of the two loss events happening? 2. Is the probability of both successfully forcing the door and fire breaking out lower than 0.05? 3. What is the most risky event in which *Inhabitant* participates, assuming that *Lock is Locked*? 4. What is the minimal risk level associated with the OaR *Door*, given all the events/actions in which it participates? In Sec. 5 we will make these queries more formal via our logic (ODGLog) and query language (ODGLang).

Definition 1 (Object-Oriented Disruption Graph). An Object-Oriented Disruption Graph (ODG) G is a tuple (A, F, O, B) where A is an attack tree, F is a fault tree, O is an object graph and B is a disruption knowledge base.

As mentioned in [34], ATs and FTs can be syntactically unified under the *disruption tree* (DT) model:

Definition 2 (Disruption Tree). A disruption tree (DT) T is a tuple (N, E, t) where (N, E) is a rooted directed acyclic graph, and $t: N \rightarrow \{\text{OR}, \text{AND}, \text{LEAF}\}$ is a

function s.t. for $v \in N$, it holds that $t(v)=\text{LEAF}$ iff v is a leaf. Moreover, $ch: N \rightarrow 2^N$ gives the set of children of a node and T has a unique root, i.e., R_T .

We also define the set of intermediate events $\text{IE} = N \setminus \text{LEAF}$. Moreover, if $u \in ch(v)$ then u is called a *child* of v , and v is a *parent* of u . Furthermore, we employ only AND- and OR-gates in the AT/FT components of the model. The behaviour of a DT T can be expressed through its *structure function* [30] - f_T : if we assume the convention that a LEAF has value 1 if disrupted and 0 if operational, the structure function indicates the status of the root node – or *top level event* (TLE) – given the status of all the LEAVES of T . Thus, for each set of LEAVES we can identify its characteristic vector \vec{b} : we refer to this vector as a *scenario*. We denote by $\mathcal{S}_T = 2^{\text{LEAF}_T}$ the universe of scenarios of T . When further distinction is needed between ATs and FTs constructs, we use (respectively) the subscripts $_A$ and $_F$: e.g., we refer to a scenario on an AT (resp. FT) as an *attack scenario* (resp. *fault scenario*), represented by \vec{b}_A (resp. \vec{b}_F). As shown before, in FT- and AT-related literature nodes canonically represent respectively *events* and *attack steps*: one might easily map *attack steps* and *events* to the terminology chosen in the COVER ontology, for which nodes N_A of an AT represent *Actions* and nodes N_F of a FT represent *Events*. From this point on, we will use the general term *elements* to refer indistinctly to nodes in FTs and ATs. To enrich ATs and FTs, we introduce *Objects at Risk* (OaRs) that explicitly capture impacted objects in (safety and security) risk experiences. These serve as a formal ground to account for the *parthood* and *participation* relations highlighted in COVER.

Definition 3 (Object Graph). An object graph (OG) O is a rooted directed acyclic graph (N_O, E_O, OP, cOP) where: 1. nodes in N_O represent Objects at Risk (OaRs); 2. directed edges in $E_O \subseteq N_O \times N_O$ represent the parthood relation between OaRs; 3. properties on OaRs are atomic propositions $op \in OP$; and 4. $cOP: N_O \rightarrow 2^{OP}$ returns a set of atomic propositions of a node $v \in N_O$.

Moreover, $ch: N_O \rightarrow 2^{N_O}$ gives the set of *parts* of a node and O has a unique root, denoted R_O . As previously hinted, OaRs and the object graph (OG) are represented by connected blue circles (see Fig. 3, page 6). Similarly to DTs' evaluation, we need a way to evaluate properties of OaRs, thus:

Definition 4 (Evaluating Properties of OaRs). We let a configuration \vec{b}_O be the Boolean vector assigning values to properties of OaRs in OP and we let $f_O: \mathbb{B}^n \times OP \rightarrow \mathbb{B}$ be a valuation such that $f_O(\vec{b}_O, op) = 1$ iff the Boolean value of a property $op \in OP$ equals 1 given \vec{b}_O .

Furthermore, we let \mathcal{C} be the set of all possible configurations. Finally, we introduce a *Disruption Knowledge Base* (DKB) that establishes a formal relation between elements in ATs and FTs and OaRs that can participate in them. We also define attribution of an impact value to ATs and FTs elements and their *preconditions* and *conditions* in the DKB. *Preconditions* are relevant properties of OaRs that can participate in a given event/action. These properties must be arranged in a specific way for events/actions to happen: *conditions* express this arrangement of *preconditions*.

Example 1. Consider the excerpt of the ODG of Fig. 3 in Fig. 4: conditions for the event *Fire breaks out* – in blue, connected with a dashed line – are encoded in the Boolean formula $\neg \text{House_Sprinklers} \wedge \text{Inhab_Unaware}$: in fact, the OaRs *House* and *Inhabitant* participate in the event *Fire breaks out* and the relevant properties of these participating objects at risk are *House_Sprinklers* and *Inhab_Unaware*. These are exactly the *preconditions* for event *Fire breaks out* and they must be set resp. to *false* and *true* in conjunction for *Fire breaks out* to happen.

Definition 5 (Disruption Knowledge Base). A disruption knowledge base (DKB) B is a tuple (D, Im, Pa, Pr) where: 1. $D = N_A \cup N_F \cup N_O$ is an entity domain where N_A, N_F and N_O are pairwise disjoint 2. $Im: N_A \cup N_F \rightarrow \mathbb{R}_{\geq 0}$ is a function that returns an impact factor for each element $v \in N_A \cup N_F$ 3. $Pa: N_A \cup N_F \rightarrow 2^{N_O}$ is a function that for each element $v \in N_A \cup N_F$ returns a set of OaRs that can participate in v 4. For each element $v \in N_A \cup N_F$, $Pr: N_A \cup N_F \hookrightarrow 2^{OP}$ is a partial function that returns the set of its preconditions $Pr(v) = cOP(o_1) \cup cOP(o_2) \dots \cup cOP(o_n)$ with $o_i \in Pa(v)$ 5. For each element $v \in N_A \cup N_F$, conditions on v are represented by a Boolean formula $Cond(v)$ over its preconditions $Pr(v)$

Do note that *conditions* naturally map to *descriptions of situations* in COVER. **Assumption 1:** Moreover, we assume that attribution of impact on parent elements (see item 2) is independent of the attribution on children elements. COVER grounds this assumption by clearly distinguishing the notions of *probability*, *impact*, and *risk*. On ODGs we propagate disruption (i.e., attacks/failures propagation in the system) and – quantitatively – their probability values. In the case of disruption likelihood, the values assigned to each event depend on those assigned to the other events to which they are related.

Differently, impact values are assigned independently to each single event. For example, the probability value assigned to a “breaking laptop” event naturally depends on the probability value of a possible related event such as “stumbling”. This is not the case for what concerns the loss value (or associated impact) of the two events (in itself, stumbling may not be a problem, while laptop breaking represents something serious). **Assumption 2:** We also assume that OaRs that can participate in parent elements (events/actions) – being decorated with AND-gates or OR-gates in the DT – are a collection of all OaRs that can participate in their children elements, plus additional OaRs added by the risk assessor (exactly what the Pa function returns). This assumption is in line with the representation of events in COVER. In this context, events modelled as children of other events in the graph can be naturally taken as parts of the parent event, and in a simplified view, this allows inferring that objects that participate in parts (or sub-events) of an event, also participate in the event itself. As seen with properties of OaRs, we need a way to evaluate whether conditions on a given DT element (it being an action or an event) are satisfied:

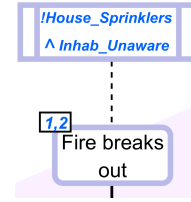


Figure 4: An excerpt of Fig. 3.

Definition 6 (Evaluating Conditions of Elements). We let $f_{Cond}: \mathbb{B}^n \times Form \rightarrow \mathbb{B}$ be the evaluation function for conditions – with $Form$ being the set of Boolean formulae – such that given a configuration \vec{b}_O and conditions $Cond(v)$ for an element v , $f_{Cond}(\vec{b}_O, Cond(v)) = 1$ iff the Boolean assignment in \vec{b}_O satisfies $Cond(v)$.

To summarize: for each element v we construct a Boolean formula $Cond(v)$ over the set of preconditions $Pr(v)$, which are exactly the relevant *properties* of OaRs that *participate* in v which are needed for v to happen. To do so, we collect the n OaRs that can participate in v with $Pa(v)$ and – for each of these objects $o_i \in \{o_1, \dots, o_n\}$ – we collect its *properties* via $cOP(o_i)$. **Assumption 3:** For each OaR that participates in element (event/action) v , we assume that its parts participate in v as well, but the opposite does *not* hold. For instance, if *Door* participates in *Door stays locked* also its part – namely, *Lock* – participates in it, but if *Lock* participates in *Lock breaking* this does not imply that *Door* participates in that event. This is, again, aligned with the theory about events, objects and their parts encoded by UFO and inherited by COVER[‡]. The union of all these collected sets $cOP(o_i)$ is exactly the set $Pr(v)$ of *preconditions* on v . The Boolean formula $Cond(v)$ over preconditions in $Pr(v)$ for v represents its *conditions*. It is important to note that, in a practical setting, a user would iteratively be asked whether 1. all participating objects in v and 2. all preconditions of a given participating OaR are relevant for conditions on v . E.g., the property *Lock_Locked* is relevant for preconditions of an element $v = Attacker\ enters\ door\ left\ unlocked$, but *Lock_Pick-able* is not: thus, it is not included as an atom in $Cond(v)$.

As hinted, understanding computations on ODGs requires further attention on the interplay between Actions (resp. Events) in ATs (resp. FTs) and their conditions. Since $Cond(v)$ is a Boolean formula over preconditions for $v \in N_A$ (resp. $v \in N_F$), for v to be attacked (to fail) the entire Boolean formula composed by $v \wedge Cond(v)$ must evaluate to *true*. To account for this, let us define an extended structure function for DTs:

Definition 7 (Extended Structure Function). The extended structure function of a disruption tree T is a function $f_T^\circ: \mathbb{B}^n \times \mathbb{B}^n \times N \rightarrow \mathbb{B}$ that takes as input a scenario \vec{b} , a configuration \vec{b}_O and an arbitrary element $v \in N$. We define it as follows:

$$f_T^\circ(\vec{b}, \vec{b}_O, v) = \begin{cases} b_i \wedge f_{Cond}(\vec{b}_O, Cond(v)) & \text{if } v = v_i \in \text{LEAF} \\ \bigvee_{v' \in ch(v)} f_T^\circ(\vec{b}, \vec{b}_O, v') \wedge f_{Cond}(\vec{b}_O, Cond(v)) & \text{if } v \in \text{IE and } t(v) = \text{OR} \\ \bigwedge_{v' \in ch(v)} f_T^\circ(\vec{b}, \vec{b}_O, v') \wedge f_{Cond}(\vec{b}_O, Cond(v)) & \text{if } v \in \text{IE and } t(v) = \text{AND} \end{cases}$$

For v to be disrupted, then, it would be necessary to have $f_T^\circ(\vec{b}, \vec{b}_O, v)$ return 1.

4 ODGLog: a Logic to reason about ODGs

We construct our logic on three syntactic layers, represented with ϕ , ψ and ξ . Layer 1 formulae reason about disruption propagation: the atomic propositions a in ODGLog can represent any element in an AT or FT, and any property of OaRs, i.e., $a \in N_A \cup N_F \cup OP$. Formulae can be combined through usual Boolean

[‡]For a more detailed focus on this assumption we refer the reader to [14, 12].

connectives. Furthermore, we can set evidence to construct what-if scenarios: $\phi[a \mapsto \text{bool}]$ sets the element a in ϕ to either 0 or 1, representing an event/action taking place or an object property being *true* or *false*. Finally, ODGLog allows reasoning about *minimal risk scenarios* (MRSs): minimal assignments on leaves of the FT and AT, such that a formula is satisfied (e.g., such that an event/action takes place). Note that MRSs are always evaluated by fixing a specific configuration, i.e. a specific status of object properties. Layer 2 formulae reason about disruption propagation probabilities. We can check whether the disruption probability of a given ϕ formula (e.g., a given event/action) is bounded by a selected threshold – with our comparison operator $\bowtie \in \{<, \leq, =, \geq, >\}$ – and we can also set probabilistic evidence, i.e., formulate scenarios where an event/action $e \in N_A \cup N_F$ is assigned a specific disruption probability q . Combining layer 2 formulae with Boolean operators is also allowed. Lastly, layer 3 reasons about safety- and security-related risk levels. One can ask what are the most risky actions/events in which an OaR participates – with $*$ $\in \{A, F\}$ symbolizing resp. AT and FT nodes, i.e., actions and events. Moreover, one can ask what is the max/min total risk level to which an OaR is subject, aggregating risk from both safety- and security-related events/actions in which it participates, and what is the optimal configuration of object properties to minimise risk on an OaR. Finally, one can also set evidence on object properties, i.e., forcefully set them to *true* or *false* to create insightful what-if scenarios. Note that when setting evidence we usually assign values to $a \in \text{BE} \cup \text{BAS} \cup \text{OP}$ in layer 1, and to $e \in \text{BE} \cup \text{BAS}$ in layer 2. We can however assign values to IEs of ATs and FTs if 1. $a/e \in N_A \cup N_F$ is a module [8], i.e., all paths between descendants of a/e and the rest of the AT or FT pass through a/e 2. and none of the descendants of a/e are present in the formula. If so, we prune that (sub)AT or (sub)FT (and relative conditions) and treat occurring IEs as LEAVES. We can formally define the syntax for ODGLog as follows:

Layer 1: $\phi ::= a \mid \neg\phi \mid \phi \wedge \phi \mid \phi[a \mapsto \text{bool}] \mid \text{MRS}(\phi)$

Layer 2: $\psi ::= P(\phi) \bowtie p \mid \neg\psi \mid \psi \wedge \psi \mid \psi[e \mapsto q]$

Layer 3: $\xi ::= \text{MostRisky}_*(o) \mid \text{TotalRisk}(o) \mid \underset{\max}{\text{TotalRisk}}(o) \mid \underset{\min}{\text{TotalRisk}}(o) \mid \text{OptimalConf}(o) \mid \xi[op \mapsto \text{bool}]$

5 Object-Oriented Risk Queries: ODGLog and ODGLang

In this section, we showcase how practitioners could ask object-oriented questions via ODGLog and present our intermediate query language, ODGLang.

Design of ODGLang. To ease the usability of our logic, we present ODGLang, a Domain Specific Language (DSL) for ODGLog. Defining languages and tools to specify properties and requirements is common: in [7] the authors capture high-level requirements for a steam boiler system in a human-readable form with SADL. Further controlled natural languages for knowledge representation include Processable English (PENG) [36], Controlled English to Logic Translation (CELT) [27], Computer Processable Language (CPL) [5] and FRETish [6]. ODGLang is constructed by adhering to the same design philosophy of *LangPFL* – a domain specific language for FTs that was developed in the literature [24]. As for *LangPFL*, ODGLang is inspired by the aforementioned languages for their ease of use and close proximity to natural language. ODGLang expresses only a fragment of ODGLog. Notably, nesting of formulae is disallowed: we retain most

of the expressiveness of ODGLog while making property specification easier. In ODGLang, *ODG* elements are referred to with their short label and each operator in ODGLog has a counterpart in the DSL: Boolean operators, not, and, or, impl...; setting the value of *ODG* elements to Boolean or probabilistic values, set, set_prob; minimal risk scenarios MRSs, MRS[...]; operators to check disruption probability thresholds, Prob[...] \bowtie ... (note that $\bowtie \in \{<, \leq, =, \geq, >\}$); and to reason about risk levels aggregated on a given object and about risky actions/events in which this object participates, MostRiskyA[...], MostRiskyF[...], MaxTotalRisk[...], MinTotalRisk[...], OptimalConf[...]. One can specify properties in ODGLang by utilizing operators inside structured templates. Assumptions on the status of *ODG* elements can be specified under the **assume** keyword. These assumptions will be automatically integrated with the translated formula accordingly, e.g., set or set_prob will be translated with the according operators to set evidence, while other assumptions will be the antecedent of an implication. A second keyword separates specified formulae from the assumptions and dictates the desired result: **compute** and **computeall** compute and return desired values, i.e., probability values, and lists of events/actions/configurations and MRSs respectively, while **check** establishes if a specified property holds.

Object-Oriented Risk Queries. In Table 1 we exemplify some queries on the *ODG* for the locked door example in Fig. 3. We use natural language, ODGLog and showcase their respective formulation in ODGLang:

Natural Language	Property in ODGLog	ODGLang
Given that an <i>Attacker destroys the door</i> and that the <i>Fire does not break out</i> , are any of the two TLEs happening?	$TLE1 \vee TLE2$ [ADD \mapsto 1, FBO \mapsto 0]	assume: set ADD = 1 set FBO = 0 check: TLE1 or TLE2
What are all the MRSs such that both <i>Loss Events</i> happen, given that <i>Lock is Locked</i> and <i>Door is Frail</i> ?	$\llbracket TLE1 \wedge TLE2$ [LiL \mapsto 1, DiF \mapsto 1] $\rrbracket_{\#}$	assume: set LiL = 1 set DiF = 1 computeall: MRS[TLE1 and TLE2]
Is the probability of both successfully forcing the door and fire breaking out lower than 0.05?	$\text{Prob}(AFD \wedge FBO) < 0.05$	assume: check: Prob[AFD and FBO] < 0.05
What is the most risky event in which <i>Inhabitant</i> participates, assuming that <i>Lock is Locked</i> ?	$\text{MostRisky}_F(\text{Inhab.})[\text{LiL} \mapsto 1]$	assume: set LiL = 1 computeall: MostRiskyF[Inhab.]
What is the max risk level associated with the OaR <i>Door</i> , given all the events/actions in which it participates?	$\text{TotalRisk}_{\max}(\text{Door})$	assume: compute: MaxTotalRisk[Door]
What is the minimum risk level on <i>Door</i> , assuming that OaR <i>Lock</i> exhibits property <i>Lock Pick-able</i> ?	$\text{TotalRisk}_{\min}(\text{Door})[\text{LP} \mapsto 1]$	assume: set LP = 1 compute: MinTotalRisk[Door]
What are the properties that all OaRs must exhibit, in order to minimise the risk level associated with the object <i>House</i> , assuming we fix that <i>Door is Frail</i> ?	$\text{OptimalConf}(\text{House})[\text{DiF} \mapsto 1]$	assume: set DiF = 1 computeall: OptimalConf[House]

Table 1: Risk queries for G (Fig. 3) in natural language, ODGLog and ODGLang.

6 Enabling Risk Computations: ODGLog Semantics

To enable object-oriented risk computations and to ground the meaning of formulae into the enriched model presented in Sec. 3, we define formal semantics

for ODGLog. For the first layer of the logic, formulae are evaluated on the following model $\mathcal{M} = \langle \vec{b}_R, \vec{b}_O, G \rangle$ where a *risk scenario* $\vec{b}_R = (b_1, \dots, b_k)$ is defined as $\vec{b}_R = \vec{b}_A \cup \vec{b}_F$, \vec{b}_O is a configuration and G is an ODG. Formally:

$$\begin{aligned} \mathcal{M} \models a & \quad \text{iff} \begin{cases} \text{with } a \in N_A & f_A^\circ(\vec{b}_A, \vec{b}_O, a) = 1 \\ \text{with } a \in N_F & f_F^\circ(\vec{b}_F, \vec{b}_O, a) = 1 \\ \text{with } a \in OP & f_O(\vec{b}_O, a) = 1 \end{cases} \\ \mathcal{M} \models \neg\phi & \quad \text{iff } \mathcal{M} \not\models \phi \\ \mathcal{M} \models \phi \wedge \phi' & \quad \text{iff } \mathcal{M} \models \phi \text{ and } \mathcal{M} \models \phi' \\ \mathcal{M} \models \phi[a_i \mapsto \text{bool}] & \quad \text{iff} \begin{cases} \text{with } a_i \in N_A \cup N_F & \mathcal{M}' \models \phi \text{ with } \vec{b}_R' = (b'_1, \dots, b'_k) \in \mathcal{M}', \\ & b'_i = \text{bool} \in \mathbb{B} \text{ and } b'_j = b_j \text{ for } j \neq i \\ \text{with } a_i \in OP & \mathcal{M}' \models \phi \text{ with } \vec{b}_O' = (b'_1, \dots, b'_m) \in \mathcal{M}', \\ & b'_i = \text{bool} \in \mathbb{B} \text{ and } b'_j = b_j \text{ for } j \neq i \end{cases} \\ \mathcal{M} \models \text{MRS}(\phi) & \quad \text{iff } \vec{b}_R \in \llbracket \phi \rrbracket_{\mathcal{M}} \end{aligned}$$

With $\llbracket \phi \rrbracket_{\mathcal{M}}$ we denote the *minimal satisfaction set* of risk scenarios for ϕ , i.e., the set of minimal risk scenarios \vec{b}_R that satisfy ϕ given G . We define $\llbracket \phi \rrbracket_{\mathcal{M}}$ as follows: $\llbracket \phi \rrbracket_{\mathcal{M}} = \{ \vec{b}_R \mid \langle \vec{b}_R, \vec{b}_O, G \rangle \models \phi \wedge \nexists \vec{b}_R'. \vec{b}_R' \subseteq \vec{b}_R \wedge \langle \vec{b}_R', \vec{b}_O, G \rangle \models \phi \}$. Note that the set of all minimal risk scenarios for a given ϕ – i.e., $\llbracket \phi \rrbracket_{\mathcal{M}}$ – is always computed by fixing a specific configuration \vec{b}_O first.

Layer two formulae require the introduction of probabilities. First, we need to decorate the leaves of the AT and the FT in G with probability values. To do so, we let an *attribution on G* be a map $\alpha: \text{BAS} \cup \text{BE} \rightarrow [0, 1]$. With a slight abuse of notation, we simply write α_G for the probability attribution on both the leaves of the AT A and the FT F in G . We then let $\rho(\phi)$ define the probability of a given layer one formula ϕ . Intuitively: given ϕ and a configuration \vec{b}_O , we consider every possible fault scenario $\vec{b}_F \in \mathcal{S}_F$ on F and how that would impact truth values of FT nodes in ϕ . For each of these fault scenarios, we compute the maximal probability of successfully attacking AT nodes in ϕ under the given configuration \vec{b}_O . **Assumption 4:** Note that – with this setup – we assume the attacker already knows which FT nodes in ϕ failed. Looking at the conceptualization provided in COVER, this aligns with the composition of the “risk experience” concept, which not only accounts for the role of “passive” elements involved in the assessment of risk (e.g., “object at risk”) but also for the role of the “active” elements involved (see, for instance, the concept of “threat object” and related *threat capability*). This, then, supports the two-step representation of the assessment process we propose, where, firstly, vulnerabilities in a system are identified and, secondly, based on these, threats can be activated. In this sense, the solution allows for simulations that act as operationalizations of the concept of “risk experience”. Consequently, we let:

$$\rho(\phi, \vec{b}_O)_{A,F} = \sum_{\vec{b}_F \in \mathcal{S}_F} \text{Prob}(\vec{b}_F) \times \mathbb{P}_A(\text{Set}(\phi, \vec{b}_F, \vec{b}_O))$$

where the probability associated to each fault scenario $\vec{b}_F \in \mathcal{S}_F$ – with $v \in \text{BE}$ – is calculated via $\text{Prob}(\vec{b}_F) = \prod_{i=1}^k b_i \times \alpha(v_i) + (1 - b_i) \times (1 - \alpha(v_i))$ and where the maximal probability of successfully attacking ϕ is given by multiplying attributions on BAses in every minimal attack scenario for ϕ – $\vec{b}_A \in \llbracket \phi \rrbracket_A$ – to then take the maximum between the resulting values of these attacks. Formally:

$$\mathbb{P}_A(\phi) = \max_{\vec{b}_A \in \llbracket \phi \rrbracket_A} \prod_{v \in \vec{b}_A} \alpha(v)$$

This last step is coherent with a more general framework for multiple metric computations on ATs previously defined in [23, 25]. Finally, we account for how every possible fault scenario would impact truth values of atomic propositions of FT nodes in ϕ by recursively defining $\text{Set}(\phi, \vec{b}_F, \vec{b}_O)$, with $\vec{b}_F \in \mathcal{S}_F$:

$$\begin{aligned} \text{Set}(a, \vec{b}_F, \vec{b}_O) &= \begin{cases} \text{with } a \in N_A & a \\ \text{with } a \in N_F & \begin{cases} 1 & \text{iff } f_F^\circ(a, \vec{b}_F, \vec{b}_O) = 1 \\ 0 & \text{otherwise} \end{cases} \\ \text{with } a \in OP & \begin{cases} 1 & \text{iff } f_O(a, \vec{b}_O) = 1 \\ 0 & \text{otherwise} \end{cases} \end{cases} \\ \text{Set}(\neg\phi, \vec{b}_F, \vec{b}_O) &= \neg\text{Set}(\phi, \vec{b}_F, \vec{b}_O) \\ \text{Set}(\phi \wedge \phi', \vec{b}_F, \vec{b}_O) &= \text{Set}(\phi, \vec{b}_F, \vec{b}_O) \wedge \text{Set}(\phi', \vec{b}_F, \vec{b}_O) \\ \text{Set}(\phi[a_i \mapsto \text{bool}], \vec{b}_F, \vec{b}_O) &= \text{Set}(\phi, \vec{b}_F, \vec{b}_O)[a_i \mapsto \text{bool}] \\ \text{Set}(\text{MRS}(\phi), \vec{b}_F, \vec{b}_O) &= \text{MRS}(\text{Set}(\phi, \vec{b}_F, \vec{b}_O)) \end{aligned}$$

where 1 and 0 represent the *true* and *false* derived layer 1 formulae. Note that – also due to Set – some occurrences can lead to the application of the \mathbb{P}_A function to either *true* or *false*, i.e., when $\phi = 1$ or $\phi = 0$. In these cases, we fix that $\mathbb{P}_A(1) = 1$ and $\mathbb{P}_A(0) = 0$. With $\bowtie \in \{<, \leq, =, \geq, >\}$ and an updated model $\mathbf{M} = \langle \vec{b}_O, G, \alpha_G \rangle$, semantics for layer two formulae can be defined as follows:

$$\begin{aligned} \mathbf{M} \models \text{P}(\phi) \bowtie p &\text{ iff } \rho(\phi, \vec{b}_O)_{A,F} \bowtie p; & \mathbf{M} \models \neg\psi &\text{ iff } \mathbf{M} \not\models \psi; \\ \mathbf{M} \models \psi \wedge \psi' &\text{ iff } \mathbf{M} \models \psi \text{ and } \mathbf{M} \models \psi'; \\ \mathbf{M} \models \psi[e_i \mapsto q] &\text{ iff } \mathbf{M}(\alpha_G[\text{with } \alpha(v_i) \mapsto q]) \models \psi, \text{ with } v_i \in N_A \cup N_F \end{aligned}$$

Note that the model \mathbf{M} for layer 2 formulae does not contain a risk scenario \vec{b}_R : this is because in computing probabilities we already account for both 1. possible fault scenarios \vec{b}_F and 2. possible attack scenarios \vec{b}_A . Layer 3 formulae require further attention on OaRs and the participation relation. To compute the risk level associated with an OaR o , given a certain configuration – e.g., the risk level of *Door*, given that *Lock_Locked* is set to *false* – we first identify the *set of elements in which o participates, and for which a satisfying risk scenario plus configuration exist*. We can consider events/actions as layer one atomic formulae a s.t. $a \in N_A \cup N_F$, and – with $*$ $\in \{A, F\}$ – formally define this set as:

$$\llbracket o \rrbracket_* = \left\{ a \in N_* \mid o \in Pa(a) \wedge \exists \vec{b}_*, \vec{b}_O. f_*^\circ(\vec{b}_*, \vec{b}_O, a) = 1 \right\}$$

Note that one might want to parameterize some elements of the given configuration \vec{b}_O to, e.g., compute optimal assignments to minimize risk on a given OaR. To accommodate for this need, we let $\mathcal{C}_{[op \mapsto bool]}$ be the set of configurations that could still be compatible with a partial Boolean assignment $[op \mapsto bool]$. E.g.:

Example 2. Assume we want to consider only the configurations compatible with setting the evidence that *Lock_Locked* is *true*, i.e., $[Lock_Locked \mapsto 1]$ and that we only have two other object properties to consider, the values of which are still not assigned. The resulting partial configuration can be represented as $\vec{b}_O = (1, \cdot, \cdot)$, where \cdot represents the unassigned values of remaining object properties. The set $\mathcal{C}_{[Lock_Locked \mapsto 1]}$ would then contain all possible configurations whose assignments are still compatible with $\vec{b}_O = (1, \cdot, \cdot)$: e.g., $\vec{b}'_O = (1, 1, 0)$ would be in $\mathcal{C}_{[Lock_Locked \mapsto 1]}$, while $\vec{b}''_O = (0, 1, 0)$ would be excluded from the set since the value of the first object property is set to zero (against $[Lock_Locked \mapsto 1]$).

We let $\text{objRiskVal} = \sum_{a \in \{\circ\}_A \cup \{\circ\}_F} (\rho(a, \vec{b}_O)_{A,F} \times \text{Im}(a))$ represent the cumulative risk value on a specific OaR o , given events and actions in which it participates. Intuitively, we sum the risk values from each event/action in which o participates, resulting from the probability of each event/action times its impact factor. Given a set of configurations \mathcal{C} , we let $\text{Val}_{\mathcal{C}}$ define semantics for layer 3 formulae:

$$\begin{aligned} \text{Val}_{\mathcal{C}}(\text{MostRisky}_A(o)) &= \operatorname{argmax}_{a \in \{\circ\}_A} \max_{\vec{b}_O \in \mathcal{C}} (\rho(a, \vec{b}_O)_{A,F} \times \text{Im}(a)); \\ \text{Val}_{\mathcal{C}}(\text{MostRisky}_F(o)) &= \operatorname{argmax}_{a \in \{\circ\}_F} \max_{\vec{b}_O \in \mathcal{C}} (\rho(a, \vec{b}_O)_{A,F} \times \text{Im}(a)); \\ \text{Val}_{\mathcal{C}}\left(\text{TotalRisk}(o)\right)_{\max} &= \max_{\vec{b}_O \in \mathcal{C}} \text{objRiskVal}; & \text{Val}_{\mathcal{C}}\left(\text{TotalRisk}(o)\right)_{\min} &= \min_{\vec{b}_O \in \mathcal{C}} \text{objRiskVal}; \\ \text{Val}_{\mathcal{C}}(\text{OptimalConf}(o)) &= \operatorname{argmin}_{\vec{b}_O \in \mathcal{C}} \text{objRiskVal}; & \text{Val}_{\mathcal{C}}(\xi[op \mapsto bool]) &= \text{Val}_{\mathcal{C}_{[op \mapsto bool]}}(\xi) \end{aligned}$$

Assumption 5: Note that with semantics as given, the attacker can adapt its strategy to the node under consideration. E.g., when computing max total risk we assume the attacker can maximise the risk level for each individual node in the graph by choosing the best BASes at each iteration. We then sum risk levels derived from each of these single-node worst-case scenarios. Operating in this way gives practitioners the safest possible risk metric, as they are provided with a worst-case upper bound when computing total risk. Also here, the assumption is inspired by how the “risk experience” is represented in COVER, where the “threat capability” of a “threat object” participating in a “threat event” is always directly related to “loss events” and related risks.

7 Conclusion and future work

We presented DODGE, a hybrid ontology-aware framework for object-oriented risk assessment that exploits both the strengths of model-based formal methods and ontologies: by combining ontologies with probabilistic risk quantification models, we enriched the expressive power of FTs and ATs and presented a more expressive ontology-aware model (ODGs), logic (ODGLog) and a query language (ODGLang). We chose COVER for its domain-independent nature and its foundation in a comprehensive analysis of existing work on risk ontologies. However,

our approach remains flexible and does not preclude the integration of knowledge from other ontologies. Our research opens up interesting directions for future work. First, one could allow a more nuanced notion of propagation considering the parthood relationship of OaRs and mereology. Furthermore, one could enrich ODGs by introducing new concepts from (the COVER) ontology, e.g., the notion of *goal*, or by introducing multiple *risk assessors* viewpoints via multiple ATs and FTs components. Finally, one could consider the effect of weakening assumptions, e.g., *assumption 3* to account for the principle of mereological expansion or *assumption 4*, on risk computation: this would increase flexibility in modelling disruptive situations while remaining ontologically grounded.

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