Towards Conceptualizing and Modelling Critical Flows - A Three-Tier Modelling Framework with a Swedish Example

Josefin Lindström[a] and Jonas Johansson[a,b]
[a] Division of Risk Management and Societal Safety, Lund University, Sweden
[b] Centre for Critical Infrastructure Protection Research (CenCIP), Lund University, Sweden
josefin.lindstrom@risk.lth.se and jonas.johansson@risk.lth.se

Abstract: Continuous access to flows of goods and services, such as energy, transport, information, and food, is essential and the basis for functioning modern societies. Hence, they are critical and need to be secured. Mega-trends such as climate change, changing geopolitical environment, hybrid- and cyber threats, and rapid technological advances come with new challenges and emerging threats to securing flows. Further, the interconnectedness of infrastructures, and globalization and leanness of supply chains, add complexity and infer increased vulnerabilities and risks to our critical flows. Given the complexities involved in securing critical flows, the focus should not only be on protection but also on resilience. Critical flows are of heterogeneous nature. They can take vastly different forms, consist of various entities, such as people, goods, energy, or data; span different geographical scales, from local to global; require an array of different physical infrastructures and supply chains. Comprehensive overview and understanding of the interdependent structure and connectivity of critical flows are largely lacking, in turn presenting difficulty in establishing a common flow concept and enabling holistic modelling and simulation approaches. In this paper, we outline a conceptual foundation and an initial modelling and simulation approach to, on an aggregated level, grasp the nature and behavior of an array of flows and their interdependencies. In this paper, the main contributions are 1) a conceptualization of critical flows applicable for analysis of a wide variety of vital societal flows by focusing on salient properties, 2) outlining of a generic model for simulation and analysis of interconnected flows, and 3) an illustration of the approach in a Swedish setting concerning flows of food, transportation, and energy, by analyzing their interdependent behavior and vulnerabilities. The proposed approach contributes toward holistically understanding and analyzing critical flows; however, many research gaps still exist.

1. INTRODUCTION

Flows of food, energy, information, and people are in constant movement across the globe. The disruption or shortage in flows in any country hence have the potential to lead to global consequences. The coronavirus pandemic has, for instance, proven the intrinsic vulnerabilities to internationalized trade, especially in combination with external hazards. Container shortages leading to disruptions in transport systems, lack of personal protective equipment in the health care sector due to a sudden rise in global demand, and shortage of agricultural workers due to closed borders are all examples that show the importance of securing our societal flows [1]. This especially holds true for those flows that have important implications for the health and safety of people and the functionality, safety, and security of our societies in short- and long-term perspectives. Examples include food, water, energy, transportation, communication, and health services. We denote these *critical flows*. The concept of critical flows is trying to, in an abstract manner, focus on goods and services essential for the functioning of societies in a holistic manner. In brief, this concept hence complements the policy agendas of critical infrastructures, which tends to emphasize on more detailed levels of the form and functions of infrastructures and their physical interdependencies; supply chain management, which tends to emphasize specific flows relating to organizations (often private); and security of supply, which tends to emphasize geopolitical concerns and international perspectives [2]. Flows generally traverse several societal sectors and have, in recent years, gained attention as an important perspective in the critical infrastructure resilience setting, particularly in the Nordic context [3]. Meanwhile, societal sectors are administrative categorizations, and neither flows nor crises are concerned with their boundaries. The construct of critical flows, in essence, aims at shifting the focus toward interdependencies between various societal entities, critical infrastructures, and supply chains.

This paper proposes an approach that aims to answer questions targeting an aggregated level of flow disturbances and their associated consequences in national and regional contexts. Examples of such questions could be: How would critical flows in society be affected if the most important import/export harbors in a country were cut off due to attacks by foreign powers? How many days of disruption of energy flows can be tolerated before severely impacting food provision? Which regions in a nation are most vulnerable to flow disturbances? How does disruption of a particular flow cascade, through the existence of interdependencies, to other flows?

In this paper, we explore if the adoption of a flow perspective could be a valuable and complementing perspective, particularly while addressing *interdependencies* between societal sectors and their associated provision of goods and services. The aim of this article is to, in an exploratory manner, to (1) present a conceptual foundation for quantitative and qualitative analyses of critical flows (2) a three-tier modelling framework for critical flows, and (3) demonstrating a Tier 1 model with an illustrative vulnerability analysis of three interdependent critical flows in a Swedish setting. First, a background of the research area and the conceptual foundation of critical flows i presented. After this, the modelling framework is described and applied to Swedish interdependent food, transport, and energy flows. The paper ends with a brief discussion on opportunities, research challenges, and future work.

2. BACKGROUND AND CONCEPTUAL FOUNDATION

2.1. Origin and relevance of critical flows

Critical flows are imperative for the functioning of society. These flows are upheld and enabled by critical infrastructures (CIs) and hence tightly interlinked with this policy and research area. It is generally acknowledged that critical infrastructures are highly interdependent upon each other [4], [5] and that ungoverned systemic risks from a holistic system-of-systems perspective might lead to severe cascading effects [6]. Critical infrastructure safety and security are often addressed and regulated on a sectoral basis, for example, within the energy sector, the transport sector, or the health care sector, meaning that despite their interdependent nature they are, in essence, governed in silo structures [7], [8]. The lack of vertical integration of regulating and managing organizations in different sectors might hinder adequate addressment of hazards and vulnerabilities that put critical flows at risk.

Many attempts to address critical infrastructures from a cross-sector perspective have been put forward since the introduction of the notion of Critical Infrastructure Protection (CIP) in the US in 1996 [9], the national plan for infrastructure protection (NIPP) in the US in 2006 [10], and the first EU CIP-directive in 2008 [11]. Evaluations of the implementation of the EU directive 2018 [8] pinpointed issues related to member states' addressment of interdependencies and resilience of CIs, and a proposal for a new directive was released in December 2020 [12] in part aiming at targeting these issues. In the Nordic context, the notion of *vital societal functions* has been used in parallel as a complement to the critical infrastructure perspective [13], mainly by governmental agencies. In the US, the similar notion of *critical functions* has been adopted in recent years to emphasize the functionality of society [10]. The above is interpreted here as signaling a need for a holistic perspective both to address cross-sectoral issues and to increase the focus on societal functionality rather than isolated infrastructural provisions. During the last decade, a shift from Critical Infrastructure Protection to a more all-encompassing Critical Infrastructure Resilience (CIR) has also occurred [3], emphasizing the need also to address the unexpected. We argue that the concept of *Critical Flows* has the potential to be valuable in addressing the challenges mentioned above since, from a flow perspective, several sectors and infrastructures are involved to ensure the continuity of a flow. See an illustration of this in Figure 1a.

2.2. Conceptual foundation

As highlighted earlier, three main academic fields deal, in part, with critical flows, but from different perspectives. These are critical infrastructure (CI), supply chain management (SCM), and security of supply (SOS), see previous work [2]. Integrating concepts and approaches from these fields can prove valuable towards securing societal functionality under various threats, as we have discussed in a previous publication [1]. The following generalized description of the three fields is hence focused on outlining differences and similarities in relation to the concept of critical flows. *Critical infrastructure* *research* usually deals with infrastructures from a security and physical point of view and from a more micro-scale perspective, e.g., focusing on structural or functional changes on the component level and how this influences the system-level behavior. An important part of the field, setting it apart from within discipline infrastructure research, is further focused on addressing interdependencies of infrastructures and how vulnerabilities, risks, and their effects can cascade between infrastructures [6], [14]. In general, this field aims at guiding decision-making with respect to resilience efforts connected to inherent physical vulnerabilities and risks of interdependent infrastructures. *Supply chain management research* tends to focus on flows of certain specific goods in greater detail and usually from a focal firm perspective [15] to, for instance, increase effectiveness and efficiency in the trade routes. Resilience in supply chains is also primarily targeted from an optimization perspective for increasing competitive advantage, and models used are often attempting to be realistic and detailed; hence a more holistic macro or meta-perspective is lacking [16]. Here, the focus is on capturing dependencies between actors or tiers of the chain [17]. Supply chain management and critical infrastructure research hence, in general terms, share the micro-scale perspectives. *Security of supply research*, on the other hand, focuses on macro level perspectives. This line of research tends to focus on geopolitical vulnerabilities and risks [18], where national and international energy balances [19], strategic material supply, and macro-trends [20] are taken into consideration. This field captures the criticality of the supply of certain flow categories (with an emphasis on energy) on a more aggregated international or global level.

Critical flows, as we see it, is hence a concept of perceived importance for different academic fields, all contributing with different valuable perspectives in describing the commonalities between flows on an aggregated level. Such commonalities are both of structural form (topology, flow volumes, temporal and spatial aspects) and functional form (flow routes, interdependencies, and capacities). However, the main characteristic that differs critical flows from the three fields is that, in our conceptualization, it operates in-between the micro and macro levels, on a complementing meso-level [2]. This meso-level approach utilizes data and integrates salient properties from both micro and macro-level approaches, aiming at enabling cross-sectoral flow studies at the granularity level of nations and regions. The concept further aims to facilitate the integration of cross-sectoral interdependencies beyond physical infrastructures and individual businesses to capture a holistic picture of societal functionality under various threats and hazards.

The concept of critical flows is contextualized in a security setting as mentioned earlier. *Securing* critical flow*s* requires both *protection* against *external hazards*, such as *natural* hazards (e.g., floods, storms, pandemics) and *man-made* crises (e.g., financial crises, antagonism, terrorism) and *resilience* to intrinsic risks and vulnerabilities (such as lack of robustness or recovery capability) and risk and vulnerabilities that emerge from interactions of the complex systems (such as interdependency-related vulnerabilities). In the present paper, we are taking the perspectives of anticipation, robustness, recovery, and adaptation as important aspects of resilience [21]. For critical flow security, three distinct contexts can be outlined. The first context is the *peacetime civil society*, where society here includes the vital societal functions and the citizens. The second context is the *civil defense*, referring to securing supply to the same vital societal functions and citizens) but in the context of heightened alert, hybrid threats, or war-like situations. The third context is securing supplies to the *military defense*, as they depend on critical flows under civil control in the context of war. The framework primarily aims to support the two former contexts, i.e. securing critical flows under normal peace-time circumstances and under various heightened levels of threats. Figure 1b illustrates the integral research fields, perspectives, and contexts relevant to the conceptualization of critical flows.

2.3. Previous work and research gaps related to modelling critical flows

Along the lines proposed here, flows have been previously discussed in the academic literature. For example, Sweijs et al. [22] present a terminology for flows in an abstract sense, where they point out four components of flows: 1) flows need to be constituted of something *(particles)*, whether its points of data or entities of goods, 2) flows need to be transported in something *(domains)*, whether it is a pipeline, a road or in cyberspace 3) flows need to move from and to some locations *(hubs),* and 4) flows need a propulsive force to be able to move *(vectors)* emphasizing that flows must be supplied, moved by and through something, to somewhere. The terminology is empirically discussed in the Dutch setting, however not further analyzed or modelled. Flow security, or sometimes critical flow security, has also been discussed in terms of e.g. long-term global trends, national strategic challenges, state and transnational actors, security and defense policies, and geopolitics for global commons and flows, by e.g. [3], [20], [22], [23]. Various types of models relating to flows have also been proposed. However, they tend to be models focusing more narrowly on technical infrastructure perspectives and their interdependent behavior [14], [24], flows relevant from an organizational perspective relating to supply chains [16], or geopolitical resource balances from an international or global perspective [19], [25]. Hence, some aspects of flows are well covered in the research literature. Certain infrastructures or supply chains can be analyzed with great detail and from several perspectives, and geopolitical affairs and global overarching import/export balance can be addressed. However, to our knowledge, there exists a research gap relating to modelling national and regional cross-sectoral flow interdependencies from a holistic and meso-level point-of-view.

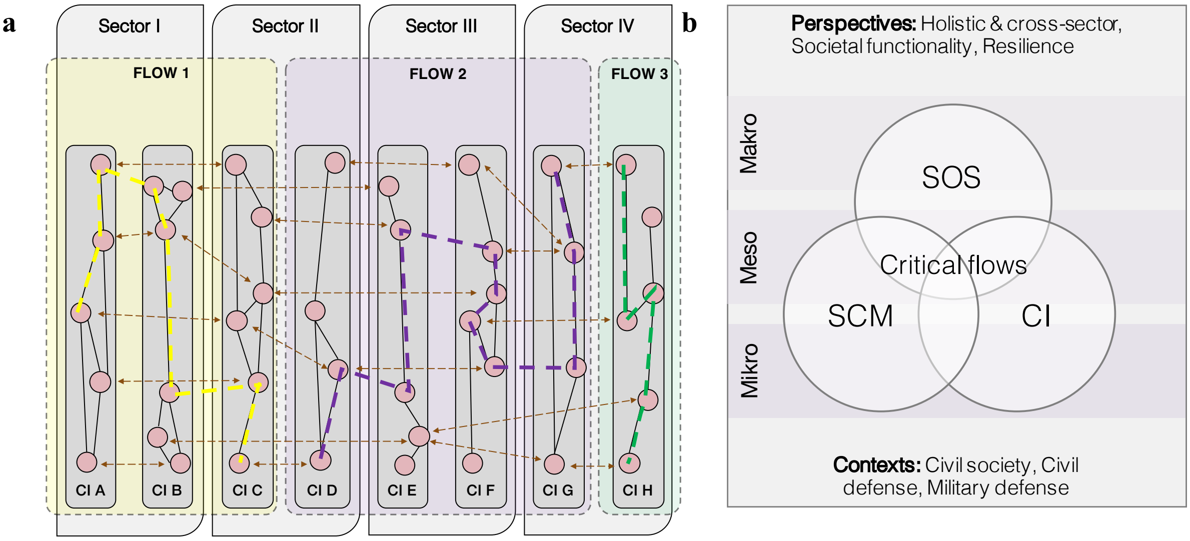

Figure 1. Illustrations of **a)** flows traversing sectors and CIs, where the arrows symbolize interdependencies between sectors and the dashed lines signify flow paths, and **b)** conceptual and contextual foundation of critical flows in relation to the research fields of critical infrastructures (CI), supply chain management (SCM) and security of supply (SOS).

3. MODELLING FRAMEWORK

A modelling and simulation (M&S) approach is here taken to operationalize the concept of Critical Flows towards guiding policy and governance efforts in improving resilience. The modelling approach aims to capture and describe salient properties of critical flows and their interdependent behavior to achieve a holistic systems-of-systems perspective. A broad interpretation of what constitutes a flow is utilized in this approach to accommodate and integrate a wide variety of flows in the same framework. This will facilitate populating a model with a broad range of data and enable a multitude of resilience-oriented analyses through simulations. The overarching aim is to systematically contrast and compare risks and vulnerabilities across different interdependent flows.

The modelling framework is aimed at guiding the construction of suitable models with respect to the availability of data and the type of questions the model is driven to answer. Three tiers of model granularity are proposed, where tiers two and three include their predecessors. Each tier has different data requirements and model granularity, allowing for different analysis and security dimensions. Each tier is further divided into three overarching categories: structural, functional, and interdependency. Table 1 outlines three proposed tiers, including examples of model parameters, threat/analysis perspectives and resilience dimensions. As the research is currently in an explorative stage, a generic Tier 1 model is detailed below and then exemplified for a Swedish case.

Structural model: Modelling of *individual flow networks* is based on a network theoretical approach [26], [27] with two types of model components: nodes (flow origin and destination) and edges (network intraconnections between nodes). Each node is here further associated with georeferences to be able to capture spatial dimensions. In the Tier 1 model, edges are not associated with additional data.

Each flow network is represented by three main constitutional parts: *supply* (import and production), *distribution* (distribution availability by the presence of edges), and *demand* (end-use and export).

Functional model: The functional model describes the behavior of individual flow networks given conditions and constraints. The functional model utilizes a breadth-first-search (BFS) algorithm [28], attempting to mimic realistic distribution patterns of physical flows. First, local node supply and demand are determined. Then the functional model distributes available supply to demand nodes via the shortest path, given that the individual flow network has distribution availability. A network can either gain supply and demand from other networks for distribution or offset its supply or demand to other networks for distribution through the interdependency model. The functional model is run sequentially for each flow present in the model.

Interdependency model: Flow interdependencies between different flow networks are modelled via the interdependency model, and can be either one-way or bi-directional. Interdependencies between two different flow networks capture the possibility for a flow to either transfer, *transfer dependency*, some or all of its supply or demand to other networks (i.e. utilize another network's distribution services) or describe dependence on services, *service dependency*, from other networks (i.e. affecting either supply, distribution or demand of the dependent network). Transfer dependencies are modelled as the availability of transfer links between nodes of two flow networks, including conversion of eventual differing flow units. Note here that a network can have several transfer dependencies to other networks; in that case, the transfers of services and demands are solved in a pre-determined order. Service dependencies are modelled as a necessity of the availability of a flow from another network to enable production, end-use, import, or export.

Table 1. Proposed model tiers. Each tier includes its predecessor.

Tier	*Structural*	*Functional*	*Interdependency*	*Main threat/analysis perspectives*	*Main resilience dimensions*
1	-Production nodes -Import nodes -End-use nodes -Export nodes -Edges (flow intraconnections) -Georeferences	-Salient flow behaviour	-Flow transfer interdependencies -Flow service interdependencies	-Structural threats, e.g. random or targeted attacks -Functional threats, e.g. closed borders, production limitations	-Anticipation -Robustness
2	-Capacities of nodes and edges -Processing nodes	- Flow behaviour including capacity constraints and processing	-Capacity of interdependencies -Geographical flow interdependencies	-Capacity related threats -Preferred path tracking	-Anticipation -Robustness -Adaptation
3	-Temporal dimensions -Stocks and buffers -Alternative production and use of flows	-Time-dependent flow behaviour with regards to alt. production, use and stock -Prioritization and ranking of paths	- Temporal dimensions -Logical flow interdependencies	-Emerging threats and future trends	-Anticipation -Robustness -Recovery -Adaptation

4. EXEMPLIFYING A TIER 1 MODEL THROUGH A SWEDISH CASE

The case focuses on flows in the sectors of food, transport, and energy in Sweden to exemplify the application of the Tier 1 model and the type of analyses it can support. These sectors are considered among the top critical in ensuring societal functionality by almost all OECD countries [4]. Further, they were selected based on their high dependence upon each other. The flows within the energy sector are restricted to diesel, the transport sector to road, and the food sector to grain to attain an illustrative case with a manageable data collection process. Figure 2a illustrates the three studied flows and their constitutional parts (supply, distribution, and demand) for each of the 21 Swedish regions (where node location corresponds to the location of each region's residential city). Figure 2b illustrates how grain and diesel flows are transfer-dependent on the road network. Table 2 presents the data used to populate the model, which is further discussed below.

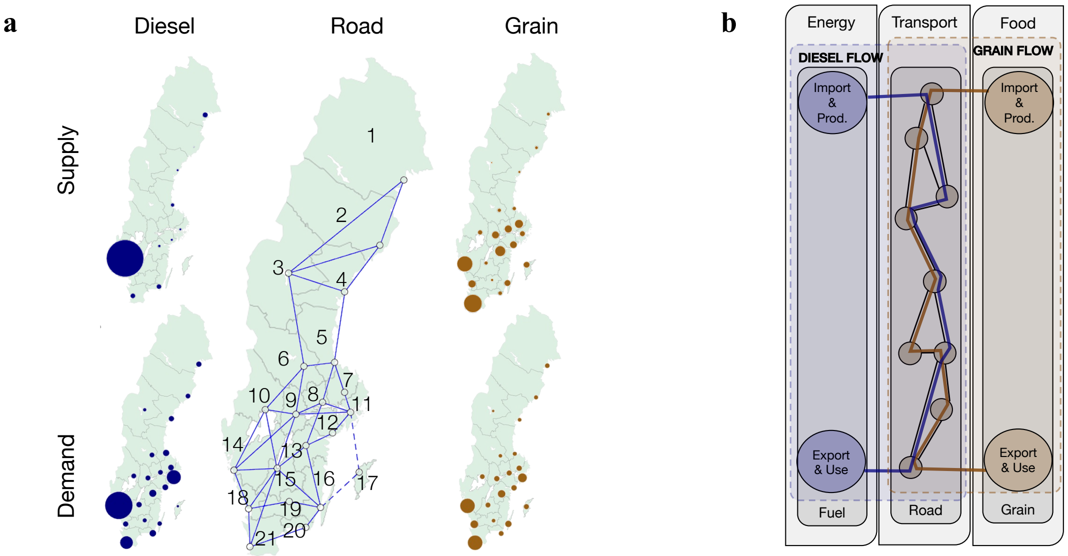

Figure 2. a) Grain and diesel supply and demand in the regions (1-21), node size illustrates relative supply and demand availability, and the road network used for distribution of these flows, and **b)** inter-sectoral illustration of the three studied flows.

Table 2. Diesel and grain data (in kilotons) for the 21 regions.

		Diesel				Grain			
#	Region	Prod.	Import	Usage	Export	Prod.	Import	Usage	Export
1	Norrbotten	135	18	117	41	13	32	63	64
2	Västerbotten	2	0	129	0	29	13	78	26
3	JämtlandHärje	0	0	62	0	7	0	37	0
4	Västernorrland	0	21	115	48	10	13	56	26
5	Gävleborg	25	42	135	96	55	6	89	13
6	Dalarna	0	0	135	0	58	0	80	0
7	Uppsala	0	0	185	0	352	0	170	0
8	Västmanland	0	0	131	0	267	6	150	13
9	Örebro	0	0	144	0	265	0	173	0
10	Värmland	0	0	133	0	100	0	137	0
11	Stockholm	0	21	1 132	47	111	19	433	38
12	Sörmland	0	25	141	56	245	6	164	13
13	Östergötland	0	32	220	74	539	6	329	13
14	V. Götaland	7 221*	1 602	818	3666	1 071	179	923	362
15	Jönköping	0	0	172	0	56	0	148	0
16	Kalmar	0	0	116	0	187	0	244	0
17	Gotland	0	0	29	0	169	13	131	26
18	Halland	0	0	159	0	262	13	332	26
19	Kronoberg	0	0	95	0	28	0	83	0
20	Blekinge	50	76	75	175	51	19	101	38
21	Skåne	0	130	657	297	1 556	114	1060	231
	Sweden, total	**7 432**	**1 968**	**4 900**	**4 500**	**5 430**	**439**	**4 981**	**888**
	Balance	*Supply = 9 400*		*Demand = 9 400*		*Supply. = 5 869*		*Demand = 5 869*	
	**Whereof 6 750 tons are fossil fuel and 471 tons are biofuel. All other figures in this column represent biofuel.*								

4.1. Context, data and population of model

Sweden has a population of around 10 million people, with a large majority living in the southernmost third of the country. Roughly half of the population is further concentrated in three metropolitan regions out of 21 regions in total: Stockholm (23%), Gothenburg (17%), and Malmö (12%). Hence the demand for goods and services is unevenly distributed spatially as well. In the model, the geographical resolution used is the 21 administrative Swedish regions, enabling analyses of flow vulnerabilities from both a national and regional perspective. The majority of the data used to populate the model is part of the Swedish official statistics collected by the Swedish Board of Agriculture [29], Statistics Sweden [30], and the Swedish Energy Agency [31]. In addition, data from large industry organizations in the food sector has been consulted [32], [33].

Energy (diesel): Sweden has no oil findings and is hence heavily dependent on imports. The most significant share (around 70% in 2020, but only 40% in 2019) of the oil import comes from Norway, and smaller shares from Iran, Nigeria, USA, and Russia [34]. Crude oil can be refined into various products, and the three Swedish refineries that produce fuel are all situated in region 14 (Västra Götaland), two in Gothenburg and one in Lysekil. There was an average of 25% admixture of biofuel in the Swedish fuels as of 2021 [35]. Some bio-fuel is produced in Sweden [36], but still around 85% of the biofuel is imported [37]. The energy data is based on the total diesel use of 6.1 million m^3 in 2021, or 4 900 ktons [38] (a diesel density of 0.799 is used [39]), which is assumed to be proportional to the population in each region. The capacity of the three refineries producing fuel in Sweden is around 22.5 million m^3 of crude oil per year [40], corresponding to approximately 20 million tons (a crude oil density of 0.9 is used). From a refinery process, the diesel fraction is 33% [41]. This altogether leads to the approximation that 6 750 ktons of diesel are produced in Sweden yearly. Approximately, two-thirds of the refined oil products are exported [40], which corresponds to 4 500 ktons of diesel, assuming that the diesel export is proportional to that of refinery products [42]. The remainder is assumed to be imported to balance the total usage and export, resulting in a total of 9 400 ktons supply and demand yearly (see Table 2). The import and export are further assumed to be proportionally distributed to the managed volumes in the 10 largest oil harbours in Sweden as of 2012 [43]. In addition to fossil diesel production, all facilities producing biofuel (except for ethanol and methanol) in 2022 are accounted for [36]. Diesel has no distribution network of its own. Therefore, the distribution of fuel is modelled as directly *transfer dependent* on the road network, see Figure 2b.

Transport (road): The Swedish backbone road network consists of 11 Europe roads and 6 national roads, and goods transports on road are mainly concentrated to these roads. In 2016, a total of 181 million tons were transported domestically, of which food constituted 9% [44]. In 2021, there were 85 500 heavy trucks (>3.5 tons) in Sweden, whereof 97% were driven on diesel [45]. Domestic distribution of food is mainly carried out through road transport (60% of ton-km), while rail (19%) and maritime transport (20%) constitute smaller portions [46]. In the model, each region will be represented by a node (21 nodes), and the connections will represent the backbone road network (41 edges) see Figure 2a. Although region 17 (Gotland) is technically an island, ferry lines are here modelled as roads for example simplicity. Further, we assume that all roads have unlimited capacity unless they are blocked (either the route is functioning to 100% or to 0%) which is a simplification in the Tier 1 model. The road network has no supply or demand of its own but operates as a distribution network for both the diesel and grain networks which has *transfer dependencies* to it.

Food (grain): The primary production in Sweden consists of around 3 million hectares, divided into 85% arable land (agricultural cultivation) and 15% for grazing. Of the arable land, 39% is used for grain production (oats, wheat, barley, rye, and rye wheat) [47]. Sweden produced almost 6 million tons of grains in 2020, which can be contrasted with the potato production of nearly one million tons [47]. The agriculture situation in Sweden follows a distinct pattern – almost 90% of the food production takes place in the southern half of the country, especially in the regions 21 (Skåne), 14 (Västra Götaland), and 13 (Östergötland). Altogether, these three regions stand for almost 60% of the total grain production in Sweden. Sweden annually produces a net surplus of grain, which is exported. The majority of the food import and export takes place through maritime transport, and the largest port is located in region 14 (Gothenburg) [48]. In the model, import and export are attributed to the regions where there are ports. The food data is limited to account for production, import, end-use, and export of grain for the year July 2013-June 2014 in the unit kilotons, which sums up to around 6000 ktons annually (see Table 2). Consequently, omitting input such as food processing, perishability and stock. The inbound and outbound stock levels (around 10% of the total numbers) are included in the production and usage figures, respectively. The usage consists of the sub-categories: animal feed (56%), industrial use (16%), seed (5%) and, foodstuffs (16%). The demand is assumed to be distributed proportionally to the regional animal produce (animal feed), grain produce (seed), and population distribution (foodstuffs and industrial use). The import and export figures are based on the relative size of the total import and export of dry bulk goods for the 25 maritime ports in Sweden with the highest annual goods flows. Alike diesel, food has no distribution network of its own. Grain distribution is modelled as directly *transfer dependent* on the road network.

4.2. Analysis and results

Some flow-related vulnerabilities are easy to detect by face-value, see e.g. the maps in Figure 2. For example, it is clear that Region 14 is a key node when it comes to the diesel flow. However, it is not as clear cut to understand from what scenarios and where potential flow-related consequences will occur. To exemplify what added value an M&S-approach could have compared to sheer face-value of the collected data, some illustrative analyses have been carried out. First, we were interested in exploring regional consequences from a scenario where the import of either diesel or grain is disrupted. Import issues could arise in the event of closed borders, as was the reality in many countries during the corona crisis [1]. By utilizing the model, it was possible to determine to which extent regions would suffer consequences (see Figure 3a). Consequences in terms of both unsupplied diesel and grain occurred in 5 regions, whereof 4 in the very north; and more than half of the country's regions (11) would suffer from diesel shortage. These types of direct scenario analyses can hence provide important input for regional and national crisis management, especially when analyzing a more extensive collection of flows and each regions vulnerability to for example import and production disturbances.

A vulnerability analysis of consequences arising from structural disturbances (that is, the interdiction of a node or an edge in the structural model) of the road network was performed. The aim was to explore how these consequences propagate to the flows of grain and diesel through transfer interdependencies. The systematic analysis consisted of consecutively removing one up to all roads (edges) in a random order. A total of 100 000 such iterations was run to attain representative results. In the first tier of the model, consequences are limited to the level of the unsupplied demand of grain or diesel for each region. In Figure 3b, the results are presented on a national scale, and in Figure 4, the results are shown on a regional scale. Each region's local supply and demand is first balanced, and it is only the remaining supply that is distributed to meet remaining demand in other regions. Hence, the consequences will not reach 100% for some regions. The fact that the grain curve's maximum value (18%) is much lower than that of the diesel curve (46%) implies that the grain supply is located closer to the demand on average and less dependent on road distribution than is the diesel supply. The vulnerability analysis reveals significant differences regarding the two flows. This is mainly due to the differences in production and consumption outspread over the country. Diesel is evidently more dependent than grain on road transport to reach all parts of the country. Since grain production is more geographically scattered and the domestic production constitutes a higher share than for diesel, it is far less import dependent and less vulnerable to road disturbances. Also, there are noteworthy differences in outcomes from different combinations of roads disturbed, as shown by the intervals presented. This especially holds true for diesel, where the interdiction of only a few specific roads leads to maximum demand side consequences. For grain, this interval is considerably smaller. To sum up, this exemplifies how non-trivial differences in flow vulnerability can be analysed, already with a Tier 1 model.

The consequences arising in the different regions giving the road disturbance level also reveal interesting results. A road disturbance level of 10% (about 4 roads not in operation) is, on average, causing very limited consequences. The fraction of unmet demand in general gradually increases with the disturbance level for most regions, but not for all. Some regions are entirely self-sufficient on either grain or fuel, hence has no demand consequence independent on the level of road disturbance (white regions). It is interesting to note that different regions show different levels of vulnerability regarding the two flows, but generally speaking, the southernmost part seems to be coping better with road disturbances. However, the pattern could very well have been the reverse for other flows. Adding more flows to the model would make it possible to distinguishing and visualizing the similarities and differences in patterns between various categories of flows on a regional and national level with this analysis. On average, a 10% disturbance level of roads is coped with well on average, both nationally and regionally. However, as indicated in Figure 3b, critical combinations of few disturbed roads can cause large consequences, especially related to fuel distribution. To identify such worst-case-scenarios, an N-4 analysis was performed where all possible combinations of 4 removed roads were systematically analysed (resulting in 101 270 different scenarios). This analysis shows that roads connected to the Gothenburg region are the most crucial when it comes to supplying fuel to Sweden's 21 regions. In contrast, only a maximum of 6% unsupplied demand occurred for the grain flow.

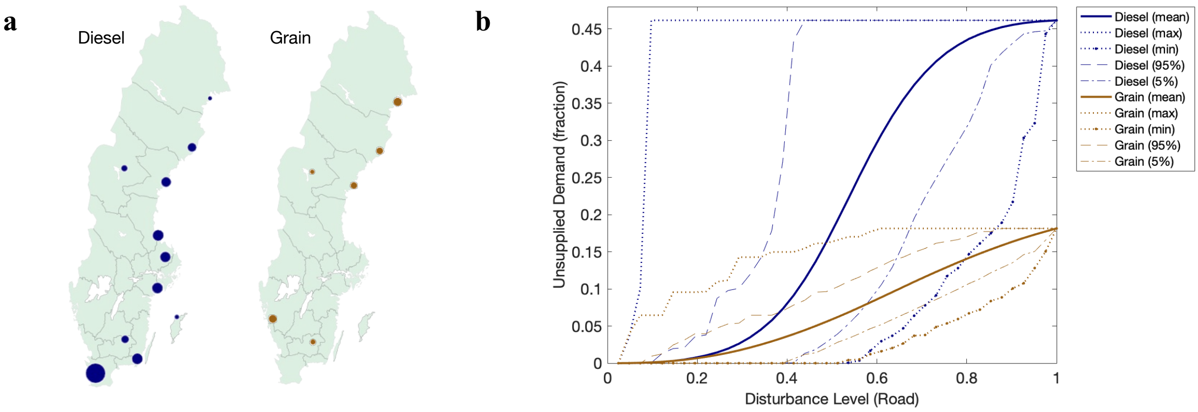

Figure 3. a) Regional consequences (unsupplied demand) in the event of import stop of diesel (left) and grain (right) **b)** Mean, max and min values, and percentiles (95 and 5) of the fraction of unmet demand for grain and diesel flows (y-axis) due to random disturbance of the road network (x-axis). Minimum, maximum and percentiles are also plotted to show the distribution of results.

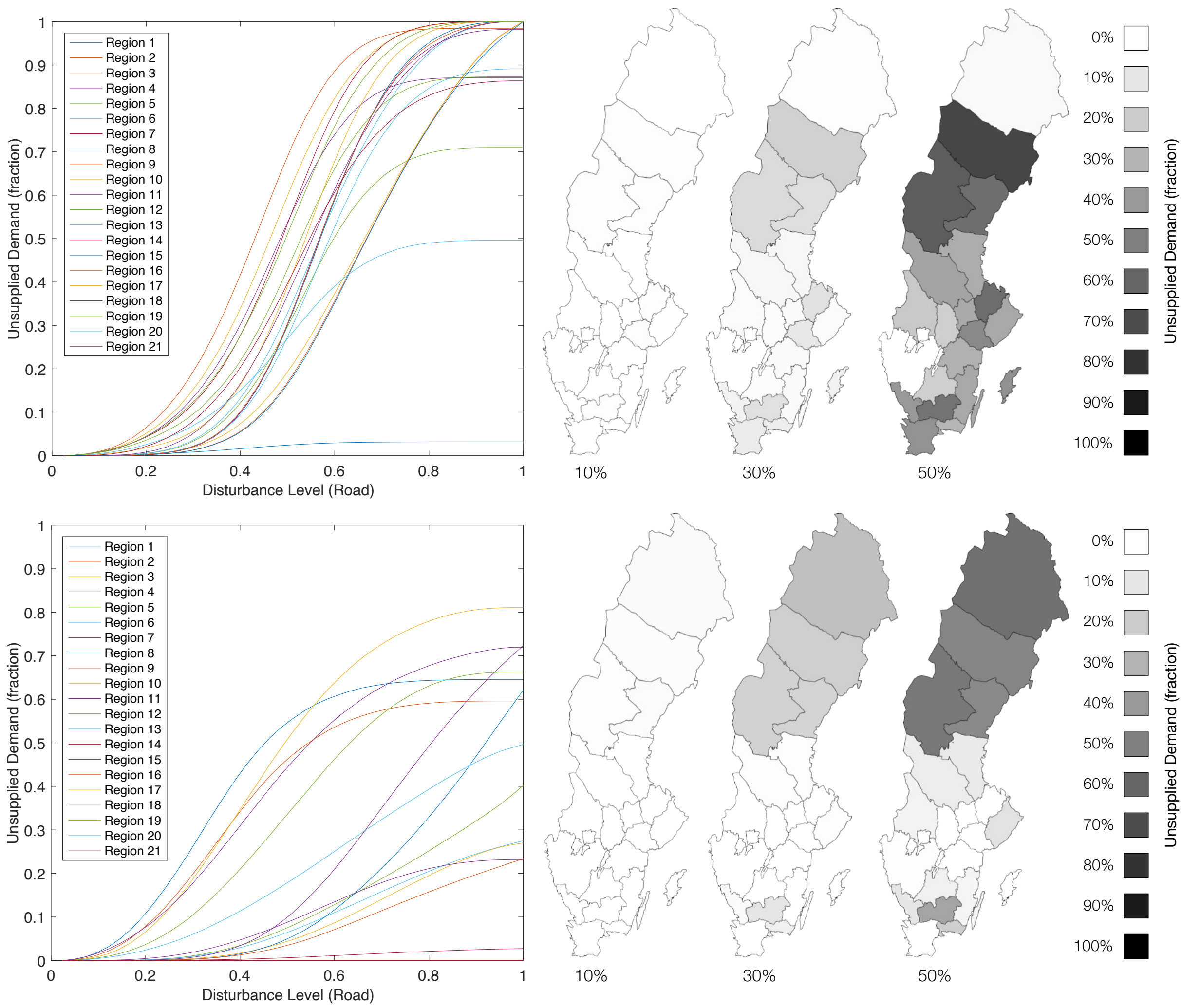

Figure 4. Consequences (unsupplied demand) for diesel (upper) and grain (lower) due to structural disturbance of the road network. Leftmost figures depict fraction of unsupplied demand (y-axis) given disturbance level of the road network (x-axis). Right figures depict these results spatially for three disturbance levels (10%, 30%, and 50%) using a linear gray-scale from 0% to 100% unmet demand.

5. DISCUSSION

Critical flow security is an increasingly important topic as signaled in various policy documents (see Section 2.1), and as shown by recent events such as the coronavirus pandemic, changing security contexts due to the ongoing Russian invasion of Ukraine (where both countries also are globally large exporters of grain), and pressing needs to adapt to a changing climate. Further, it is reasonable to think that such global trends will impact the complexity of flow security in the near future. For example, to connect to the illustrative case, the diesel market share will decrease due to the rise of electrification of road transport and the general global transition from fossil fuels. The security of critical goods and services tends to be administrated mainly within specific societal sectors, e.g. monitored and regulated by different authorities, hence lacking overarching governance of the independent behavior of critical flows. Further, the form and function of various flows are usually unique, where the resilience of different types of flows, e.g. food versus electricity, are not easily contrasted or compared. Therefore, a large part of the underlying work behind this article is to define a generic critical flow concept and identify commonalities (salient properties) across a wide variety of flows. The conceptualization is here used as input to the proposed modelling framework and scrutinized through a Swedish case. By establishing a generic meso-level view and modelling approach for critical flows, we believe that it can aid in addressing pressing issues. Issues such as identifying flow vulnerabilities, upstream and downstream consequences of flow interdependencies, and ranking and prioritization of flows. Naturally, focusing on a meso-level generic approach comes with some drawbacks in accuracy and precision. However, we argue that what is lost in terms of details is won in terms of achieving a more holistic picture; capturing cross-sectoral flow interdependencies, and enabling contrasting and comparison of vulnerabilities and risks across various types of flows.

The present paper is part of an ongoing exploratory research project, where the model presented will be continuously iterated and refined based on the three-tier modelling framework. The presented Tier 1 model was exemplified in a Swedish case, demonstrating that even a Tier 1 model enables valuable holistic analyses for exploring flow vulnerabilities and interdependencies. Collecting data and analyzing a wider variety of flow networks of food, energy, transport, healthcare, information and communication will hence facilitate an understanding of flows in our complex societies across sectoral administrative borders and infrastructures. This includes addressing flow transfer dependencies, allowing for analyses of alternative flow modes, prioritization of flows, and capturing emergent interdependent flow behaviors of severely disturbed flows. Since still being on the first tier of development, the model contains several simplifications. One major simplification is that distribution edges have unlimited capacity, which inevitably leads to an underestimation of consequences and vulnerabilities. In reality, if several backbone roads are disturbed this would very likely lead to congestions and delays throughout the system in varying degrees. Another simplification is that stocks and buffers are not yet implemented, which usually acts as dampeners for flow disturbances (within and across flows). However, stocks and buffers gets depleted over time and flows can also consist of perishable goods (such as food) or of other time-critical values which calls for inclusion of temporal dimensions in the model. Therefore, in future versions of the modelling approach, we intend as a first step to include capacity limitations where routes or resources can be partly limited to capture better the impact of different threat situations (from civil contingencies to military threats) and as a second step include temporal dimensions.

Nevertheless, the Tier 1 model approach has, despite its simplifications, shown to generate non-trivial and valid results by enabling analyses of three inherently different flows in a Swedish case. The focus of the presented analyses is on vulnerability as a subpart of resilience. This focus enables systematic exploration of particular situations or scenarios that can cause significant societal consequences. The consequences in the case are only captured as unsupplied demand of the different flows on national and regional levels. From the case example, we can note that a 50% disturbance level of the road network would lead to unsupplied demand of diesel by 19% on average, while only 6% on average for grain. However, which other overall societal consequences would arise from such a shortage and the long-term effects is also of essence to explore. Further for the studied flows, much more intricate dependencies exist. For example, domestic diesel production is heavily dependent on importing crude oil from various sources, where the maritime transport network provides the transport services needed. The trucks dispatching the diesel are, in turn, driven on diesel, in essence a bi-directional interdependency between the two flow types. Transport of fuel and grain is to some degree also carried out with other transport modes, meaning that it is probably possible to relocate parts of the flows on roads to railway or maritime transport. A more nuanced picture could be captured in future versions by explicitly modelling these additional flow networks and their transfer dependencies.

Many research challenges exist in attaining a holistic picture of critical flows. One considerable difficulty is collecting and aggregating appropriate data to populate a more all-encompassing model, which already proved challenging for the relatively small illustrative example presented here. It required a considerable data collection and many assumptions to populate the generic model. For example, we needed to consult with Statistics Sweden to ensure data consistency and correct interpretations of some of the data. However, the generic model forces data aggregation and processing to be systematic and consistent.

As argued in this paper, there is a need for a more holistic perspective of critical flows supplying society with essential goods and services. Addressing these issues from a meso-perspective is illustrated as useful in bridging cross-sectoral resilience and interdependency issues on regional and national levels. Further, by advancing the notion of critical flows and employing more large-scale and detailed analyses, this line of research will help illustrate the importance of taking a holistic perspective and give evidence on our critical flows in guiding decision- and policymaking.

6. CONCLUSION

This paper has provided a conceptual foundation for *Critical Flows* – a meso-level concept argued to be of relevance due to the increased interdependencies and complexity of critical infrastructures, supply chains, and vital societal functions. The conceptual foundation is operationalized in a proposed three-tier modelling framework, where an initial Tier 1 model is exemplified in vulnerability analyses of interdependent Swedish food, transport, and energy flows. The meso-level approach integrates data and outlines salient properties of importance from existing micro-level (critical infrastructure and supply chain research) and macro-level approaches (security of supply research), enabling cross-sectoral flow studies at the granularity level of countries and regions. We conclude, although the work is in an early stage and further research is needed, that the approach holds promise in supporting efforts towards ensuring resilient critical flows.

Acknowledgements

We greatly acknowledge the Swedish Civil Contingencies Agency (MSB) for funding the research through the project "Critical Flows" (2018-90034).

References

[1] J. Lindström and J. Johansson, *'How Corona Crisis Affects Critical Flows -- A Swedish Perspective'*, in Proc. of the 31th European Safety and Reliability Conference (ESREL), Angers, France, pp. 2986–2993, (2021).

[2] J. Lindström and J. Johansson, *'Towards understanding critical flows'*, Proc. of the 30th European Safety and Reliability Conference and 15th Probabilistic Safety Assessment and Management Conference (PSAM), (2020).

[3] Aula et al., *'Critical Nordic Flows - Collaboration between Finland, Norway and Sweden on Security of Supply and Critical Infrastructure Protection'*. National Emergency Supply Agency, Helsinki, (2020).

[4] OECD, '*Good Governance for Critical Infrastructure Resilience'*, (2019).

[5] S. M. Rinaldi, J. P. Peerenboom, and T. K. Kelly, *'Identifying, understanding, and analyzing critical infrastructure interdependencies*', IEEE Control Syst. Mag., vol. 21, no. 6, pp. 11–25, (2001).

[6] J. Johansson, H. Hassel, A. Cedergren, L. Svegrup, and B. Arvidsson, *'Method for describing and analysing cascading effects in past events: Initial conclusions and findings'*, Safety and Reliability of Complex Engineering Systems – Proceedings of the 25th European Safety and Reliability Conference, pp. 4423–4431, (2015).

[7] T. Rydén Sonesson, J. Johansson, and A. Cedergren, '*Governance and interdependencies of critical infrastructures: Exploring mechanisms for cross-sector resilience'*, Safety Science, vol. 142, no. April. (2021)

[8] European Commission, *'Commission staff working document. Evaluation of council directive 2008/114 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection'*, Brussels, Belgium, (2019).

[9] The White House, *'The President Executive Order 13010 - Critical Infrastructure Protection'*, (1996).

[10] Homeland Security, *'NIPP – the National Infrastructure Protection Plan'*, (2006).

[11] European Council, *'On the identification and designation of European critical infrastructures and the assessment of the need to improve their protection (Council Directive 2008/114/EC)'*, (2008).

[12] European Commission. *'Proposal for a Directive of the European Parliament and of the Council on the resilience of critical entities'*. COM(2020) 829 final. Brussel, Belgium, (2020).

[13] C. Pursiainen, *'Critical infrastructure resilience: A Nordic model in the making?'*, Int. J. of Disaster Risk Reduction., vol. 27, no. 653390, pp. 632–641, (2018).
[14] M. Ouyang, *'Review on modeling and simulation of interdependent critical infrastructure systems'*, Reliability Engineering and Systems Safety, vol. 121, pp. 43–60, (2014).
[15] M. Frostenson and F. Prenkert, *'Sustainable supply chain management when focal firms are complex: A network perspective'*, J. Clean. Prod., vol. 107, pp. 85–94, (2015).
[16] J. Pires Ribeiro and A. Barbosa-Povoa, *'Supply Chain Resilience: Definitions and quantitative modelling approaches – A literature review'*, Comput. Ind. Eng., vol. 115, no. November 2017, pp. 109–122, (2018).
[17] J. D. Lambert, Douglas M, Cooper, Martha C, Pagh, *'Supply Chain Management: implementation issues & research opportunities'*, Int. J. Logist. Manag., vol. 9, no. 2, pp. 1–19, (1998).
[18] A. Correljé and C. van der Linde, *'Energy supply security and geopolitics: A European perspective'*, Energy Policy, vol. 34, no. 5, pp. 532–543, (2006).
[19] T. Rokicki and A. Perkowska, *'Diversity and changes in the energy balance in EU countries'*, Energies, 14(4), (2021).
[20] E. Brattberg and D. S. Hamilton, *'Global Flow Security - A New Security Agenda for the Transatlantic Community in 2030'*. Washington DC, (2014).
[21] S. Hosseini, K. Barker, and J. E. Ramirez-Marquez, *'A review of definitions and measures of system resilience'*, Reliability Engineering and System Safety, vol. 145, pp. 47–61, (2016).
[22] T. Sweijs, et al. *'Flow Security, Dutch Defense and Security Policies'*, Hague Center for Strategic Studies, pp. 1–82, (2018).
[23] M. Aaltola, J. Käpylä, H. Mikkola, and T. Behr, *'Towards the Geopolitics of Flows: Implications for Finland'*. The Finnish Institute of International Affairs (2014).
[24] E. S. Hub, *'Geospatial Risk and Resilience Assessment Platform - GRRASP'*. [Online]. Available: https://joint-research-centre.ec.europa.eu/geospatial-risk-and-resilience-assessment-platform-grrasp_en. [Accessed: 25-Feb-2022].
[25] J. W. Mellor, *'Global food balances and food security'*, World Dev., vol. 16, no. 9, pp. 997–1011, (1988).
[26] M. Newman, *'Networks: An Introduction'*. Oxford University Press, (2010).
[27] J. Johansson and H. Hassel, *'An approach for modelling interdependent infrastructures in the context of vulnerability analysis'*, Reliab. Eng. Syst. Saf., vol. 95, no. 12, pp. 1335–1344, (2010).
[28] S. Larocca, J. Johansson, H. Hassel & S. Guikema, *'Topological Performance Measures as Surrogates for Physical Flow Models for Risk and Vulnerability Analysis for Electric Power Systems'*, Risk Anal., 35(4), pp. 608–623, (2015).
[29] Swedish Board of Agriculture, *'Statistikdatabasen'*, 2022. [Online]. Available: https://jordbruksverket.se/om-jordbruksverket/jordbruksverkets-officiella-statistik/statistikdatabasen. [Accessed: 14-Feb-2022].
[30] Statistics Sweden, '*Hitta statistik'*. [Online]. Available: https://scb.se/hitta-statistik/. [Accessed: 14-Feb-2022].
[31] Energimyndigheten,*'Statistik'*. [Online]. Available: www.energimyndigheten.se/statistik/ [Accessed: 14-Feb-2022].
[32] Lantmännen, *'Störst i Sverige på spannmålsexport'*.
[33] Agronomics, *'Agronomics'* [Online]. www.agronomic.se. [Accessed: 14-Feb-2022].
[34] Energimyndigheten, *'Drivmedel 2020'*, ER 2021:29, (2021).
[35] Miljöbarometern, *'Andel förnybara drivmedel i vägtrafiken, indikatorer för fossiloberoende transporter år 2030*', (2021).
[36] Bioenergitidningen, *'Biodrivmedel i Norden 2022'*, (2022).
[37] Preem, *'Det svenska importundret'*. [Online]. Available: www.preem.se/om-preem/om-oss/det-svenska-importundret/ [Accessed: 01-Mar-2022].
[38] Drivkraft Sverige*, 'Volymer', Utlevererad volym av oljeprodukter och förnybara drivmedel*', (2021). [Online]. Available: https://drivkraftsverige.se/statistik/volymer/. [Accessed: 01-Mar-2022].
[39] V. Kumbár and J. Votava, *'Effect of the rapeseed oil methyl ester component on conventional diesel fuel properties'*, Sci. Agric. Bohem., vol. 45, no. 4, pp. 254–258, (2014).
[40] Preem, *'Europas modernaste raffinaderier'*, (2019). [Online]. Available: https://www.preem.se/om-preem/om-oss/vad-vi-gor/raff/. [Accessed: 01-Mar-2022].
[41] V. Lindström et al., *'En studie om förnybara drivmedel och dess förutsättningar i norra Sverige'*, (2017).
[42] Preem, *'Varuförsörjning'*. [Online]. Available: https://www.preem.se/om-preem/om-oss/vad-vi-gor/varuforsorjning/. [Accessed: 02-Mar-2022].
[43] P. Adolfsson, *'De största oljehamnarna'*, Sjöfartstidningen, (2014).
[44] Trafikanalys, *'Varuflödesundersökningen 2016'*, (2017).
[45] Trafikanalys, *'Fordon i län och kommuner 2021'*, (2022).
[46] Trafikanalys, *'Svenska godstransportflöden - modellberäkningar'*, (2016).
[47] Jordbruksverket, *'Jordbruksmarkens användning 2020. Slutlig statistik'*, (2020).
[48] Göteborgs Hamn, *'Så funkar det: Export över Göteborgs Hamn'*, (2013). [Online]. Available: www.goteborgshamn.se/press/nyheter/sa-funkar-det-export-over-goteborgs-hamn/. [Accessed: 03-Mar-2022].