Innovative business modelling for understanding criminal networks and illicit markets

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Abstract

Financial incentives serve as a primary motivator and enabler for organisations to engage in illicit activities, like drug trafficking. Such illicit activities often involve coercion and the use of violence. Drug trafficking, recognised as one of the most profitable criminal enterprises, also demonstrates extreme resilience and adaptability in the face of law enforcement interventions. Nonetheless, most law enforcement efforts focus primarily on disrupting the underlying logistics process and the associated criminal network.

To better capture the complexity and underlying dynamics of criminal organisations, insight is needed into the relationship between the criminal value chain (financial, logistical and social) and the impact of interventions over time. In this paper we illustrate how a computational system approach based on criminal business modelling can be used to create insight on the resilience of illicit markets. The explorative computational approach simulates how criminal organisations may adapt to different intervention strategies grounded in their underlying criminal business models. Its purpose is to stimulate critical reflection and support the development of more innovative and effective interventions.

Keywords: criminal networks, business modelling, modus operandi, critical thinking, double-loop learning.

Introduction

Criminal networks are often deeply embedded in society, seamlessly integrating illicit activities, such as drug trafficking, with legitimate operations, like investments in real estate (Dekkers, 2023) or sports (Europol, 2016). Moreover, drug trafficking is often accompanied by violence, threats and corruption, leading to a significant impact on society (Gerell et al., 2021; UNODC, 2024).

The activities of criminal networks are diverse and interconnected. For instance, drug trafficking requires a supply chain that encompasses production, transport and sales. Each of these activities is often entangled with corruption and/or intimidation (to facilitate production) and money laundering (to handle illicit proceeds). Additionally, criminal networks continuously try to stay under the radar by operating covertly and often in a decentralised manner. As a result, criminal networks are resilient (Ayling, 2009) and can adapt their modus operandi as a reaction to external factors such as law enforcement interventions. For instance, the interdiction of cocaine smuggling routes in Central America has led to adjustments in these routes to evade detection, as described by Magliocca et al. (2022). Another example of structural and functional changes in the criminal networks after law enforcement interventions can be found in O'Reilly et al. (2020). This yields a cat-and-mouse game between criminal networks and law enforcement, with both sides trying to outsmart each other.

In this sense, the embedding of criminal networks in society can be considered a complex adaptive system (Eidelson, 1997; Duijn et al. 2014). This complexity makes criminal networks resilient and challenging to disrupt. In fact, efforts to counter these criminal networks can also cause undesired effects like displacement (Magliocca et al., 2022) and even corruption (O'Reilly et al., 2020), retaliation and violence escalation. To cope with this inherent complexity, it is crucial to first analyse the system as a whole and in all its dimensions, logistical, social and financial, as highlighted by Spapens (2010). System analysis seeks to unveil the intricacies of a system, in all its dimensions, including its underlying components and interrelationships (Conger and Mason, 2013).

One component of the criminal system is the underlying financial drive. This is particularly true for organised criminal networks, as highlighted by Lotspeich (2000). Drug trafficking is particularly considered one of the most profitable criminal enterprises, as noted by May (2017). However, this perspective is often overlooked, even though criminal activities seek to make profit and rely heavily on investments, which are frequently funded by previous proceeds from other criminal activities. Recently, the need to consider more explicitly the financial aspect has been highlighted by, among others, Snaphaan and Ruitenburg (2024), Manzi and Calderoni (2024), Albanese (2023) and the Dutch Procureurs Office (Openbaar Ministerie, 2023). As suggested in Barros et al. (2024), the analysis of the criminal business model, which includes the financial, logistical and social dimensions of the criminal network, creates new insights into how these networks will adapt to protect their operations when facing law enforcement interventions. The need to develop computational models to simulate this resilience is also emphasised, promoting critical thinking to support the development of effective interventions capable of disrupting criminal networks over the long term. Van der Zwet et al. (2025) proposed an agent-based model to understand how opportunistic behaviour in criminal groups contributes to the adaptive capacity of illicit supply chains by considering these dimensions. However, such computational approaches tend to be highly abstract, whereas practitioners require models that enhance awareness and foster critical thinking. This paper responds to that need by presenting an explorative computational model.

The aim of the proposed model, rather than prediction (Epstein, 2008), is to uncover core dynamics and discover new questions that enhance awareness of the resilience of criminal networks, thereby supporting the development of more effective interventions. Furthermore, it aims to challenge law enforcement decision-makers to consider the criminal organisation as a complex adaptive system. Our model simulates different possible reactions of a criminal network to different types of interventions based on the underlying criminal business model as introduced by Barros et al. (2024). This computational approach is inspired by exploratory modelling that focuses on the development of models to enable exploring a range of possible dynamics and outcomes for decision support given the available information (Steinmann et al., 2024). It differs from the traditional modelling approach that focuses on one model to accurately describe all system characteristics and behaviour (Bankes, 1993). As such, our computational approach offers the opportunity to simulate the evolving nature of the modus operandi of criminal networks and to explore the possible impact of different intervention strategies to counter these networks over the long term. In this way, the model serves as a vehicle to stimulate double-loop learning (Argyris, 1977). Double-loop learning is particularly suitable for understanding complex criminal networks with sophisticated and evolving modus operandi. It stimulates law enforcement organisations to continuously reflect on the possible effect of their interventions and their underlying assumptions, based on new insights, changing circumstances and evolving tactics of the criminal networks. The proposed computational model supports decision-makers to better grasp the inherent complexity, which stimulates the development of more effective and sustainable law enforcement interventions.

The proposed explorative computational model differs from existing approaches like Manzi and Calderoni (2024), who examined the resilience of a cocaine trafficking organisation against law enforcement efforts targeting specific key actors. Unlike Duijn et al. (2014) and Duxbury and Haynie (2019), who analysed network characteristics to define resilience, Manzi and Calderoni (2024) propose an agent-based model to analyse the effect of police interventions targeting specific roles in the criminal network (e.g. acquisition, trafficking, packaging and selling) on the revenue of the criminal network. Each agent has a specific role and strives to successfully complete it, generating revenue for the organisation. However, the model does not consider that a criminal organisation can employ various modus operandi to adapt to policing pressure and sustain its revenue. Magliocca et al. (2024) accounted for the adaptability of the criminal organisation by formulating a coupled agent-based model with a spatial interdiction optimisation model to assess the efficiency of law enforcement interventions. In this model, agents assess the trafficking costs based on the perceived risk of a particular modus operandi. This, in turn, influences the agents' decisions regarding which trafficking routes to use for shipping drugs, thereby altering the modus operandi of the criminal organisation. However, these authors do not consider how different law enforcement interventions influence the dynamics of the costs associated with each modus operandi. Finally, Weyland et al. (2023) took the financial perspective into account, to analyse the circumstances under which an individual joins a criminal organisation based on their societal environment and financial/societal situation. This computational model used a cost–benefit agent-based model wherein the financial component was implicitly represented through a fitness function that included power, money and success. The cost–benefit trade-off analysis can also be used to analyse changes in criminal organisation activity, adaptation and resilience, as shown by van Elteren et al. (2025).

This paper is structured as follows: first, we introduce the explorative computational model using cocaine trafficking as an example. Next, we present an illustration of its potential using an example. Finally, we draw some conclusions and recommendations for future research.

Methodology

In this paper, we introduce an explorative computational model that enables the exploration of how the criminal business model is affected when subjected to different types of law enforcement interventions. The model supports decision-makers in reflecting on the underlying assumptions that guide their decisions, along with exploring the potential effects of various law enforcement intervention strategies. This approach is built on the premise of double-loop learning. Introduced by Argyris (1977) in the late 1970s, double-loop learning goes beyond simply refining the current strategy by adjusting it based on past outcomes (single-loop learning). Instead, it involves a critical reflection and reassessment of the underlying assumptions, goals and norms that drive those interventions. Double-loop learning can be stimulated through computer simulation, as shown by Kim et al. (2013). By engaging with a computer model, decision-makers can explore different strategies and obtain insight into the broader implications of their strategies within a complex environment.

The illicit market exhibits a high degree of complexity that defies intuitive comprehension of its dynamics. As discussed throughout this paper, the financial aspect plays a significant role in the dynamics of a criminal business model. To gain a better grip on this complexity, it is essential to understand the intricacies of the entire system and to encourage decision-makers to rethink their strategies or, in other words, to engage in double-loop learning. This modelling approach builds on the criminal business analysis approach proposed by Barros et al. (2024).

In this section we will first briefly describe how to conduct the analysis of the criminal business. This analysis will be used to develop our explorative computational model.

Analysis of a criminal business model

Cocaine trafficking can be viewed as a value chain involving various parties, subject to the laws of supply and demand and associated price formation mechanisms. To analyse this criminal business model, Barros et al. (2024) propose a methodology consisting of three steps. In the first step, the methodology describes how to conduct a stakeholder and value network analysis. Understanding the roles, interests and added value of each party in the value chain clarifies the relationships between the parties involved. Using these insights, the business model is further analysed for each party using a business model canvas (Osterwalder and Pigneur, 2010). The canvas provides insight into how the criminal network in question creates value, which activities and resources are needed to achieve this, what the costs are, and through which channels the product is sold and how this yields benefits. As such, the canvas offers an overview of how the business model of the criminal network works. Finally, the business model is quantified using a cost–benefit analysis that considers uncertainty. A cost–benefit analysis maps out the costs and benefits offering a method to assess the financial aspects of the business model. In this case, it focuses on analysing the total costs and benefits of the individual parties in the value chain of cocaine trafficking, for example producers, traders, dealers and brokers. This analysis is carried out by first mapping out all relevant cost and benefit items and then preferably monetising these items, that is, putting a monetary value on them, or at least quantifying them. For further detail, see Barros et al. (2024).

The analysis of the criminal business model provides insight into the areas where the parties involved can be most financially impacted. Since criminal networks are driven by financial gain, these insights can be used to identify interventions that counteract the underlying criminal business model. Additionally, it allows for the comparison of different criminal business models (and the corresponding modus operandi). This comparison can be used to identify more attractive business models and potential future frictions in the value chain in a timely manner. By doing so, it supports law enforcement intelligence and enhances its early warning capability.

Modelling criminal business models requires access to relevant data sources. Data can be retrieved, among others, from law enforcement documents and law court sentences, and from open sources like the European Union Drugs Agency (former European Monitoring Centre for Drugs and Drug Addiction (EMCDDA)), the European Union Agency for Law Enforcement Cooperation (Europol) (EMCDDA and Europol, 2022) and the United Nations Office on Drugs and Crime (UNODC) (UNODC, 2023). The data for the current modelling efforts was collected through an analysis of relevant literature for three illustrative examples of a modus operandi. In practice, the diverse and fragmented nature of the different data sources poses a challenge for the collection and structuring of the data. Moreover, to challenge the adaptiveness of criminal networks, it is required to develop rapid data collection and analysis. Advancements in AI and increased computing power provide support in the automatic extraction and analysis of unstructured sources of information to efficiently make sense of large amounts of textual information sources and extract characteristics of different modus operandi (Barros et al., 2022).

Explorative computational model

An explorative computational model has been developed to gain a deeper understanding of the dynamics of a drug trafficking criminal network. The aim of this approach is to create insight into the cost–benefit dynamics of the criminal business model, considering external factors such as law enforcement intervention. The computation model builds on the criminal business modelling approach proposed in Barros et al. (2024). The criminal business modelling methodology was applied using open sources like Europol (2024), UNODC (2023), EUDA (former EMCDDA) and Europol (2022) and Roks et al. (2021) to create three illustrative examples of cocaine trafficking business models in the Netherlands ('Dutch port', 'Dutch cocaine laundry' and in another, non-Dutch port ('EU port')). Using the model, an interactive simulation tool has been created that enables interactive analysis. This tool includes visual illustration to enhance the understanding of the possible financial evolution of the criminal business model. The proposed explorative computer simulation model invites law enforcement practitioners to explore how criminal networks might respond to different law enforcement intervention strategies. By creating a space for reflection and discovery, the use of the model encourages decision-makers to revisit underlying assumptions about cocaine trafficking and fosters double-loop learning.

Examples of criminal business models

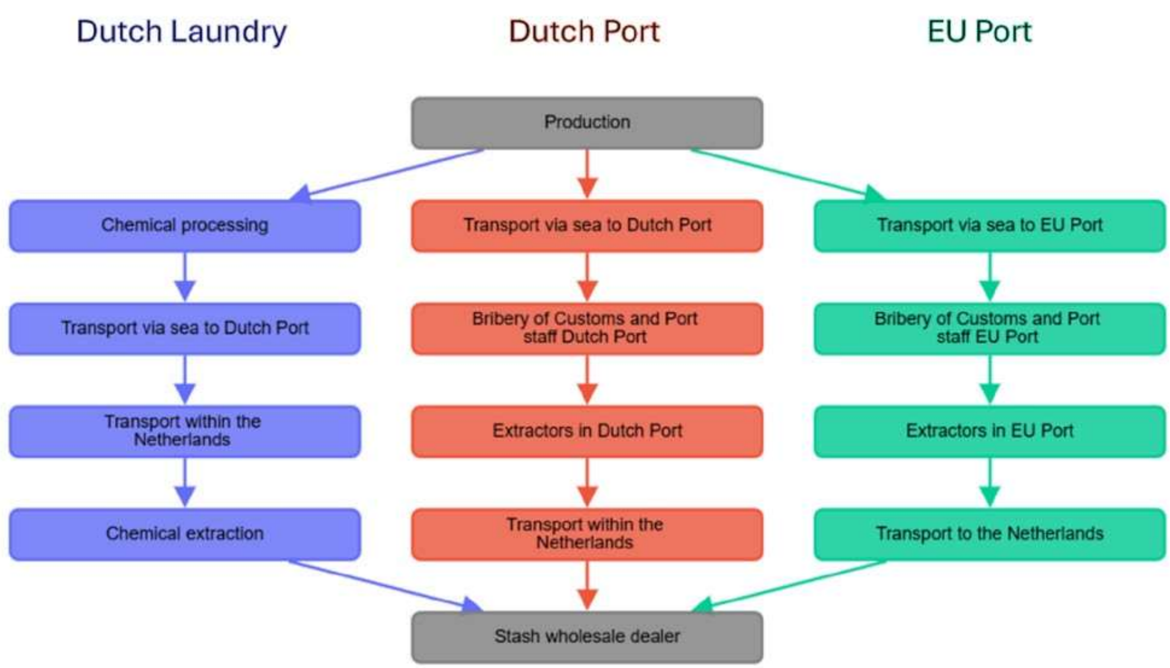

Figure 17.1. Overview of three examples of cocaine trafficking business models

Dutch port represents the first modus operandi, whereby the cocaine is concealed in ship containers and shipped from the origin country to a port in the Netherlands (see Figure 17.1). At the port, the drugs are extracted covertly from the shipping containers and taken outside of the port. This smuggling modus operandi often relies on the cooperation of the shipping company and/or port authorities and customs to avoid container inspections and to locate the containers containing cocaine, essentially involving corruption (Roks et al., 2021). The cost–benefit analysis based on open sources, using the methodology described in the previous section, shows that the costs involved with shipping container extraction are estimated to be smaller than the costs associated with the required corruption activities (Europol, 2024), and that the largest profit margins are achieved by the wholesale dealer (Barros et al., 2024).

An alternative modus operandi is the EU port, which involves adding an extra waypoint in the transportation chain to avoid arrival at a Dutch port (see Figure 17.1). In this case the shipment containing concealed drugs arrives at another EU port, which is assumed to be less monitored by law enforcement. The drugs are then extracted and transported by road to the Netherlands. The cost–benefit analysis shows that, similarly to the Dutch port business model, the costs involved with shipping container extraction are estimated to be smaller than the costs associated with the required corruption activities and that the largest profit margins are still achieved by the wholesale dealer. Due to reduced monitoring at this port, it is assumed that the costs of smuggling the cocaine into this location are smaller than at the Dutch port. However, additional transportation costs from the EU port to the Netherlands are necessary, resulting in higher overall expenses compared with the initial Dutch port business model.

Finally, to reduce the risks at the port, another modus operandi involves hiding the cocaine by impregnating it into an innocent-looking product, such as clothing, in the country of origin. This 'hiding in plain sight' strategy makes detection more difficult and eliminates the need for immediate extraction at the port. However, it requires the incorporation of the cocaine in the origin country and its extraction in the Netherlands. This extraction process corresponds to the reverse impregnation process and requires a specialised facility known as a 'laundry'. The cost–benefit analysis shows that this modus operandi, Dutch laundry, yields less costs at the port but requires additional expenses associated with the incorporation and extracting of the drugs.

The three different modus operandi result in different criminal business models and value chains that were derived using the cost–benefit analysis described in the previous section. As the price of cocaine has been stable for the last decades (RTL Nieuws, 2022), we will assume that the benefit component of the analysis is constant for the three criminal business models. Law enforcement interventions can impact the profitability of these criminal business models differently. Law enforcement interventions targeting a specific step of the value chain can increase the costs and therefore decrease the profitability of the criminal business model. For example, if law enforcement focuses on reducing corruption at the port, the risk of engaging in an illicit activity increases, pushing the bribery costs up. Similarly, for the drug extractors, the more that are caught, the higher the perceived risk becomes, which in turn can increase the costs of their illicit activities. In such a case, the Dutch port business model becomes less attractive, prompting the criminal network to adapt its cocaine trafficking modus operandi to develop a more lucrative business model, as financial gain is a major driving force.

Computational model

To analyse the dynamics of illicit drug trafficking and shed light on how targeted law enforcement interventions impact the business model, we introduce an explorative computation model based on the concept of agent-based modelling (ABM) (Bonabeau, 2002). ABM enables capturing non-linear emergent effects by simulating simple interactions between individual agents and their environment. Furthermore, ABM has proven to be a powerful tool for studying complex social systems and understanding how micro-level effects can trigger macro phenomena (Bonabeau, 2002). Therefore, ABM will be used to model how, under a specific law enforcement strategy, the business model that ultimately becomes the most lucrative can emerge over time.

The agent-based model developed is based on the criminal business models (and associated value chains) depicted in Figure 17.1. Each agent is associated with one of the criminal business models and with a specific step within the corresponding value chain. Each agent has the following attributes:

- criminal business value chain: name of the criminal business to which the agent belongs;
- initial cost: associated cost of the value chain step at the beginning of the simulation;
- current cost: current cost of the value chain step at a given iteration of the simulation;
- cost increase rate: the rate at which costs change following a law enforcement intervention (this can be linear or non-linear).

The initial cost and the cost increase rates are based on Barros et al. (2024). The initial cost is expressed as a percentage of the product's total cost, and the resulting criminal business chain value is updated linearly by simply multiplying the current cost by the corresponding cost increase rate. When an exponential rate applies, the costs are updated in a way that makes them rise progressively over time following an exponential pattern. The model parameters can be found in Table 17.1.

Table 17.1. Overview of the model parameters

Business chain value	Cost increase rate
Transport by sea to EU port	Linear
Bribery of customs and port staff in EU port	Exponential
Extractors in EU port	Linear
Transport to the Netherlands	Linear
Transport by sea to Dutch port	Linear
Bribery of customs and port staff in Dutch port	Exponential
Extractors in Dutch port	Linear
Transport within the Netherlands	Linear
Chemical processing	Linear
Transport by sea to Dutch port	Linear
Transport within the Netherlands	Linear
Chemical extraction	Exponential

The aggregation of the agents of a given criminal business model and their actions is modelled as a meta-agent. This meta-agent models the overall criminal business value chain and its overall costs. Finally, a smuggler meta-agent is modelled to represent the criminal network. For the sake of simplicity, it is assumed that this meta-agent's behaviour is rational. The smuggler will always choose the cheapest modus operandi.

In the explorative computational model, the decision-maker can choose between different law enforcement interventions for each of the three criminal business models:

- Dutch port: targeting drug extractors and/or targeting corruption at the Dutch port;
- EU port: intensifying collaboration with EU law enforcement agencies to increase monitoring and decrease corruption at the EU port;
- Dutch laundry: targeting drug laboratories responsible for the cocaine extraction.

Once the decision-maker has defined which strategies to use, including their frequencies, the explorative computational model simulates the corresponding law enforcement interventions over a two-year period. These interventions are distributed uniformly across the two-year period, using a daily time step. When a law enforcement intervention is carried out, it is assumed that the costs of the targeted criminal business step increase. The rationale behind this dynamic is that potential corrupt individuals are harder to recruit, and/or that criminals will increase their prices due to increased probability of being caught. Therefore, if the law enforcement interventions stop, this will impact the costs of the target criminal business step. In fact, if there is less risk of a law enforcement intervention, there is less need for extra mitigating measures and, as such, the associated costs will decrease. These fluctuations depend on the value of the criminal business chain step. For instance, the costs associated with employment of drug extractors (often unskilled youngsters (The Brussels Times, 2024)) to extract the cocaine from shipping containers remain relatively stable, as the supply of volunteers to carry out this illicit activity is relatively high. On the other hand, the costs associated with customs corruption can vary significantly. Contrary to the drug extractors, the customs activities that need to be corrupted are conducted by a smaller number of skilled professionals (NL Times, 2019). Additionally, an increase in law enforcement interventions targeting corruption is expected to intensify their risk perception, thereby increasing the costs associated with carrying out these illicit activities.

Each simulation of the explorative computational model covers a period of two years and models the impact of the different chosen law enforcement interventions on the profitability of the different criminal business models. Additionally, the computational model makes it possible to review the timeline and identify the criminal business model most frequently chosen over the two-year period.

As the model is intended to illustrate its potential for stimulating double-loop learning, we rely on a single simulation run at this stage. For more in-depth exploratory analysis, additional simulation runs can be easily introduced (Steinmann et al., 2024).

Results

In this section we will show how the introduced explorative computational model can be used to facilitate double-loop learning. As mentioned before, three illustrative examples of criminal business models have been implemented to prompt decision-makers to analyse potential effects of disruption strategies and gain a deeper understanding of the repercussions of their interventions against criminal networks.

The results of the different simulations are visualised to create a better awareness of how the costs, profit margins and market share of each criminal business model may evolve over time under the selected law enforcement strategy. To encourage critical reflection, decision-makers are deliberately provided with limited law enforcement resources. This constraint is intended to prompt them to think strategically about their approach and to explore how different prioritisation choices may influence the criminal business models. In this scenario, law enforcement interventions are capped at 10 units, with each unit representing an arbitrary measure of law enforcement effort. Consequently, the decision-maker can allocate these efforts across various criminal activities.

Initial scenario

The initial scenario consists of the situation where a criminal network has the means to conduct its cocaine smuggling operations via the described three different modus operandi. When no law enforcement interventions take place, the most profitable criminal business model is Dutch port (which has the largest market share), followed by EU port and finally Dutch laundry.

Drugs extractors intervention focus

Facing the initial scenario, the decision-maker is prompted to choose, for instance, whether to focus on targeting drug extractors or on countering corruption. Figure 17.2 shows that a strategy wherein all law enforcement efforts are focused on drug extractors in the Dutch port has no effect. If we assume that all the simulated interventions (against drugs extractors) result in arrests, the overall costs associated (Dutch port) remained unchanged. This outcome might be surprising, as it could be expected that successful interventions over a two-year period would decrease the attractiveness of the Dutch port business model. However, it is assumed that the extraction of drugs does not require specific knowledge or skills, resulting in a large pool of potential drugs extractors, making replacement easy. This assumption keeps the costs required to hire drug extractors stable. Consequently, the market share is expected to remain the same.

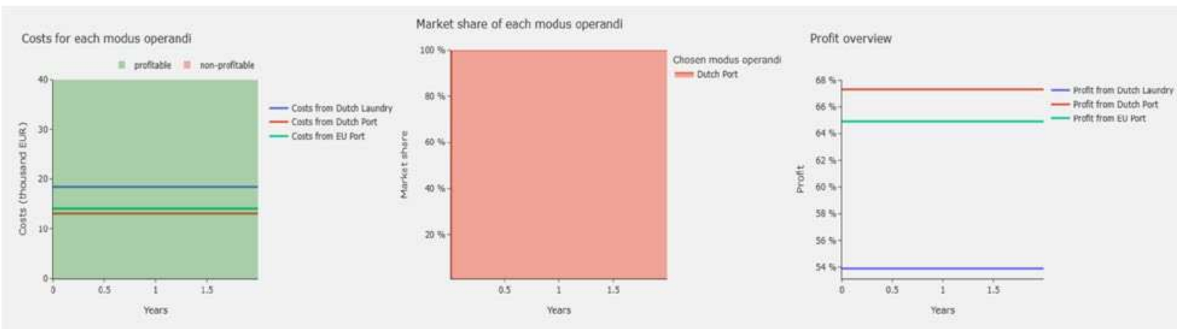

Figure 17.2. Visualisation of the simulation results based on only targeting drug extractors in the Dutch Port
NB: The evolution of the criminal business models costs (left), market share (centre) and profits (right) are shown.

These results suggest that a repressive intervention focusing on drugs extractors may not have the desired effect. They should trigger the decision-maker to consider other alternative possibilities, like exploring preventive interventions to deter individuals from engaging in drug extraction. In this sense they stimulate double-loop learning (challenge current approach and seek new strategies).

Corruption focus

Based on the previous insights, the decision-maker might be inclined to change the strategy by now targeting corruption at the Dutch port. As countering corruption requires more resources, which are usually scarce, only a limited number of law enforcement interventions can take place, for instance 10. Assuming that these investigations have led to arrests, corruption at the port will be more difficult to establish, which leads to extra costs, see Figure 17.3, for a timeline of up to two years. This also suggests that the overall costs of the Dutch port modus operandi may increase. The explorative computational model points out that this strategy may yield a shift in the market share as the alternative criminal business model via other EU ports has become now more attractive (waterbed effect).

These insights hint at the need to consider other intervention strategies. In particular, they can prompt the decision-maker to readjust the chosen strategy and switch the law enforcement efforts completely to collaboration with foreign equivalents over the following two years. These adaptations in the law enforcement strategy may yield an adaptation of the criminal business model, as Figure 17.3 shows. Between the fourth and sixth years, the EU port criminal business costs increased. As the focus on corruption at the Dutch port was stopped, the Dutch port business model costs slowly decrease. However, after six years of law enforcement interventions, the Dutch laundry business model, which had previously been spared by such interventions, becomes as attractive as the other two criminal business models (as the three yield very similar profits) (see Figure 17.3).

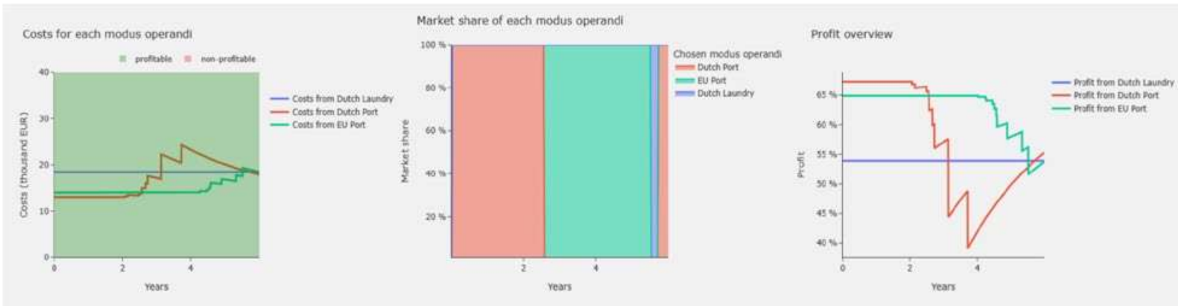

Figure 17.3. Visualisation of the simulation results when the focus of first two years of law enforcement efforts is on corruption at the Dutch Port

NB: After two years, the law enforcement strategy focuses solemnly on intensifying the collaboration with foreign law enforcement in other EU ports. The evolution of criminal business costs (left), market share (centre) and criminal business profits (right) are shown.

Contrary to the usual lean manufacturing assumption that focusing on one area of improvement at a time will achieve significant gains, the explorative model shows that with resilient criminal networks this might not lead to the expected results. Moreover, it suggests that it is important to consistently execute a given strategy to avoid creating an opportunity for the criminal network to use another modus operandi. This exemplifies the added value of this approach in questioning assumptions and stimulating double-loop learning.

Combined intervention strategy

The previous results can trigger the decision-maker to distribute the scarce law enforcement efforts evenly across the three criminal business models. As such the decision-maker can explore the possible effect of combined law enforcement strategy, wherein law enforcement efforts focus on corruption in Dutch port and EU port, and on Dutch laundry criminal business models. In this manner, the decision-maker hopes to prevent Dutch laundry from becoming the next profitable criminal business model. However, the results in the timeline between years six to eight show that a complicated pattern emerges, see Figure 17.4.

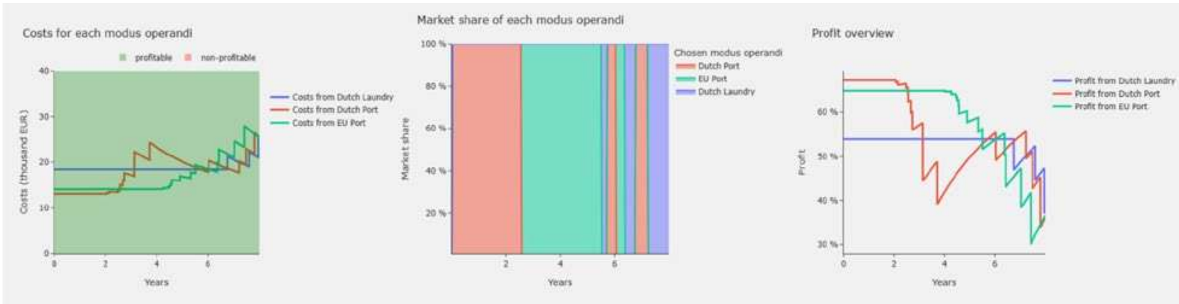

Figure 17.4. Visualisation of the simulation results when using a mixed law enforcement strategy between years six and eight on the collaboration with EU ports, countering corruption at the Dutch port and countering Dutch laundry

NB: The evolution of the criminal business costs (left), market share (centre) and criminal business profits (right) are shown.

In fact, after seven years it seems that no criminal business model remains predominant for longer than three months. One can see that after five years, the criminal business share market changes every three months, making it very difficult to anticipate which market will dominate in the future, which was not anticipated. These results stimulate reflection on the chosen strategy and, as such, double-loop learning.

Discussion

The goal of the developed explorative computational modelling approach is to support double-loop learning by encouraging decision-makers to reflect on, and explore, the possible effects of law enforcement interventions. The model helps decision-makers to think about what law enforcement interventions might lead to by letting them interact with the system's key dynamics. The possibility to conduct 'what if' analysis to explore different possible outcomes of the chosen intervention stimulates reflection and critical thinking, as explained in the results section. It is important to underline that the proposed modelling approach is designed to explore the complexity inherent in drug trafficking systems, acknowledging that the highly dynamic and adaptive nature of these social systems limits the possibility of precise prediction.

The current model assumptions and analysis show that, for the given scenario, focusing efforts on a single policy strategy and targeting a specific criminal business step might achieve the desired outcome in the short term. However, this approach may inadvertently make alternative criminal businesses models more attractive. As the results suggest, redirecting efforts to the newest lucrative criminal business model might make previously less lucrative business models attractive. Again, these results challenge the common assumption that concentrating on a single strategy yields the best results. Moreover, they also prompt the decision-maker to realise that efforts to disrupt a criminal network might unintentionally make another criminal business model more attractive, creating a cat-and-mouse dynamic. In addition, they also highlight the importance of long-term commitment and consistent execution of the chosen strategy. Finally, they also suggest that when financial gain is the primary driver for criminal networks, it may be worthwhile to consider reducing the profitability of the entire criminal business model or, in other words, to explore ways of destabilising the supply–demand system. This can be achieved not only through repressive measures but also, for instance, by demotivating consumers to using cocaine for recreational purposes.

Conclusions

This paper proposes an explorative computational modelling approach that enables law enforcement agencies to gain deeper insight into the complexity of disrupting criminal networks, using a double-loop learning approach.

The current model explicitly focuses on the financial component and the logistics associated with the criminal business model. This integrated approach provides further insight into the resilience of criminal networks, as it fills a gap in research that has been focused independently on logistics, financial transactions or the social network. Despite the profit-driven nature of criminal activities, there remains a significant gap in analysing criminal business models and the effects of criminal network disruption strategies.

The paper's contributions are built on a holistic approach that encompasses multiple aspects of the crime system. It demonstrates the potential of a simple explorative computational model to challenge decision-makers and enhance their awareness of the resilient behaviour of the entire system. By exploring the possible impact of different law enforcement strategies, the model exposes decision-makers to the possible consequences of short-term or inconsistent strategies. It also helps them realise that, rather than focusing on a single component, it may be necessary to reduce the overall attractiveness of the underlying criminal business model. In doing so, it can encourage them to consider alternative interventions, such as demotivating consumers from acquiring illicit products. Such interventions are not yet included in the explorative computational model but can be easily added. In this manner, the computational model supports double-loop learning by encouraging innovative thinking and the exploration of effective preventive and repressive law enforcement interventions capable of disrupting criminal networks over the long term.

Additionally, in contrast to other valuable analysis efforts focused on understanding and disrupting criminal networks based on either data analysis or simulation models, this interactive explorative modelling approach stimulates decision-makers to reflect on the adaptive and resilient behaviour of the criminal business models using a scenario that feels familiar and relatable. This approach enhances the potential for simultaneously stimulating double-loop learning for decision-makers who will face the complexity of criminal business models and are urged to anticipate possible (undesired) effects. It also stimulates co-creation, as it involves decision-makers in modelling efforts of future disruption strategies. The explorative modelling approach enables the incorporation of new and relevant aspects and perspectives into the explorative computation model, bridging the gap between data analysis and complex systems modelling.

Finally, further research is necessary to further fulfil the computational modelling potential, particularly for creating more detailed models, stimulating double-loop learning and identifying possible effective interventions. For example, the explorative computational model should be extended with the social network dimension to better capture the resilience of the criminal networks. Incorporating the dynamics at a social dimension would provide the possibility to further understand the effects of disruption efforts on the functioning of criminal networks. Moreover, criminal networks might merge or split to maintain covertness or increase effectiveness. Other extensions of the model could focus on including stochasticity and explicitly modelling the connections and dependencies between different illicit markets and illicit supply chains, thereby causing the tool to evolve from supporting double-loop learning toward supporting decision-making. In particular, extending the modelling approach to include multiple simulation runs could support decision-makers in generating a range of possible scenarios, enabling them to explore in more detail potential disruption efforts before these are put into practise, that is *ex ante* (Steinmann et al., 2024).

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