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Review

Resource Allocation with Karma Mechanisms—A Review

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Abstract: Monetary markets serve as established resource allocation mechanisms, typically achieving efficient solutions with limited information. However, they are susceptible to market failures, particularly under the presence of public goods, externalities, or inequality of economic power. Moreover, in many resource-allocating contexts, money faces social, ethical, and legal constraints. Consequently, artificial currencies and non-monetary markets are increasingly explored, with Karma emerging as a notable concept. Karma, a non-tradeable, resource-inherent currency for prosumer resources, operates on the principles of contribution and consumption of specific resources. It embodies fairness, near incentive compatibility, Pareto-efficiency, robustness to population heterogeneity, and can incentivize a reduction in resource scarcity. The literature on Karma is scattered across disciplines, varies in scope, and lacks conceptual clarity and coherence. Thus, this study undertakes a comprehensive review of the Karma mechanism, systematically comparing its resource allocation applications and elucidating overlooked mechanism design elements. Through a systematic mapping study, this review situates Karma within its literature context, offers a structured design parameter framework, and develops a road map for future research directions.

Keywords: resource allocation; artificial currency; non-monetary economics; systematic mapping study; karma

JEL Classification: C71; D44; D61; H41

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1. Introduction

Resource allocation mechanisms are decision-making processes about distributing limited and scarce resources among a group of recipients (Paccagnan et al. 2022). Central resource allocation involves one deciding entity, which requires a vast amount of information for this task. On the contrary, market mechanisms employ a distributed decision-making process, in which agents decide on their resource-allocating actions autonomously according to their subjective utility. Markets prove to be powerful, as they achieve near Pareto-efficient solutions with a minimal amount of information (Piccoli 2023). While barter markets are of limited practicality, monetary markets are a useful tool for resource allocation in practice, due to the use of a standardized, globally-accepted, monetary currency that can be traded in for any resource (Kregel 2021).

However, money does not always do its job, and monetary markets fail sometimes; phenomena such as inequality of economic power, public goods, and externalities, to name a few, have been observed to lead to undesirable, inefficient allocations (Bator 1995; Coase 1960; Hardin 1968; Peterson 2017). What is more, in many contexts, the use of money is not desired, socially not accepted, considered unethical, or even prohibited (e.g., donations, shared resources, collective decision-making within organizations) (Roth et al. 2004). A growing branch of literature is concerned with artificial currencies (Gorokh et al. 2021), which represent non-monetary markets and resource allocation mechanisms. For isolated, single-stage resource allocation problems, extensive work on non-monetary matching and combinatorial assignment problems has been conducted (Budish 2011; Dutot et al. 2011;

Gale and Shapley 2012; Karaenke et al. 2020; Nguyen et al. 2016; Skowron and Rzadca 2013). For repeated resource allocation problems, there are few works on non-monetary market mechanisms yet, among which Karma has evolved as an important narrative.

Karma employs a currency different from money; it can only be gained by producing and only be lost by consuming a specific resource. It is a resource-inherent, non-monetary, non-tradeable, artificial currency for prosumer resources (produced and consumed by market participants likewise). As a non-monetary mechanism, Karma complements monetary markets and provides attractive properties. For example, it is fairness-enhancing, near incentive-compatible, and robust towards population heterogeneity (Censi et al. 2019); Elokda et al. (2022, 2023). Due to the design of Karma, one can consider Karma as playing against your future self, as the only way to consume is to put effort and produce first, and future needs must be traded off against present needs when consuming. Last but not least, Karma is reported to not only concern the efficiency and fairness of resource allocation but also to lead to a decrease in resource scarcity in peer-to-peer markets (Kim et al. 2021; Prendergast 2022; Roth et al. 2004; Sönmez et al. 2020).

Let us discuss Karma with the example of public goods. The road network of a city is a shared resource, that has unrestricted access to consumption, and a diminishing marginal utility with increasing consumption for the users. Road users can unrestrictedly drive into the city, which is useful to them, as they can reach work, shopping, social, living, and recreational facilities faster when compared to other modalities. However, if too many drive by, congestion arises, and nobody moves a single inch. A well-discussed countermeasure is the introduction of monetary markets, namely: congestion pricing (De Palma and Lindsey 2011), where vehicles need to pay a surcharge for driving in the city. This leads to a decrease in the demand for the network, and to sustainable, congestion-free levels of usage. Due to the monetary disincentive, people will trade off their urgency to drive to the city, and their willingness to pay. However, congestion pricing can be problematic, as equity issues emerge in a society with unequal distribution of economic power: the poorest will most likely not be able to afford the charge and thus consume significantly less. During implementation, equity considerations are the major hurdle for congestion pricing to overcome in the political debate. Karma could make a difference here: not driving could be considered as producing, and driving could be considered as consuming the resource "right of driving to the city". Instead of paying money as a congestion pricing tax, Karma points could be used. These Karma points cannot be bought, but only gained by not consuming. This would force individuals not to trade off the price with other resources they could buy alternatively but to solely consider present versus future consumption of this specific resource. What is more, the socio-economic contexts, such as income or wealth, and therefore, related equity issues would not play a role anymore.

The literature on Karma is strongly dispersed over different fields and years. Starting with the first publication in 2003, Karma applications targeted issues on peer-to-peer computer network markets for filesharing, where free-riding (consuming files without providing content for others) was a major issue. In 2014, Karma became an important technological component for modern blockchain technologies such as cryptocurrencies, and a fairness-enhancing incentive mechanism in behavioral studies. Beginning in 2019, Karma gained momentum as an artificial currency and resource allocation mechanism in the economic discourse and is modeled as a dynamic population game. Consequently, discussions on Karma vary in scope, and lack methodological consistency and conceptual clarity, as particular mechanism design aspects might be overlooked. The diversity of Karma applications highlights the need for a systematic framework of design parameters and options. Unfortunately, to date, there is no comprehensive overview of Karma present in the literature, which urges the need for a systematic review of Karma to enhance more systematic research.

Therefore, this work aims to provide an exhaustive literature review of the Karma mechanism. The review covers an exhaustive overview and systematic comparison of Karma applications as resource allocation mechanisms, a Karma framework with design

parameters and options, discusses its game theoretic modeling and offers future research directions. Altogether, the contributions of this review can be summarized as follows: (i) This review connects Karma with the context of its literature, which enables the perception of Karma as a non-monetary, resource allocation mechanism to a broader audience. (ii) This review provides a unifying framework of existing Karma mechanism designs, which enables more systematic analysis in future studies.

The remainder of this work is as follows. Section 2 presents the research protocol and outlines the methodologies used for the literature review (systematic mapping study, Latent Dirichlet Allocation). Section 3 elaborates on the origins of the Karma mechanism and depicts the intellectual structure and trends of the Karma citing literature. Section 4 reviews the applications of Karma as a resource allocation mechanism and distills relevant mechanism design elements. Section 5 elaborates on promising future research directions for Karma-related works. The study closes with concluding remarks on Karma in Section 6.

2. Methodology

2.1. Literature Review with Systematic Mapping Study

Literature reviews are secondary studies (meta-studies), that represent a method to condense, synthesize, and survey knowledge from a large collection of primary studies. Conducting a literature review can serve a multitude of reasons: to present the current state of knowledge on a topic, to identify all evidence for or against a hypothesis, to establish where there is consensus or to debate on a scientific issue, to show how knowledge and models around a topic evolved historically, and to look out for future research directions (Aromataris and Pearson 2014).

Four cognitive biases can affect the scientific integrity of a literature review and lead to systematic errors (Wright et al. 2007). The author bias (confirmation bias) describes the threat to not include all relevant studies and to include studies in favor of the expected outcome only. The publication bias is the risk of laying too much emphasis on studies with positive results (which are usually more likely to be published) and neglecting studies with negative or inconclusive results (that often end up unpublished or not published in journals). The English language bias refers to the neglect of non-English literature. The non-reproducibility bias is the risk of not following a formal, systematic approach, which impedes independent reproduction of conclusions by others.

The three types of literature review differ in their approach, purpose, and scope (Harris et al. 2014). While the *traditional literature review* relies on the authors' knowledge, experience and network, the *systematic literature review* requires a formalized, systematic, and scientific approach to discuss a topic in a well-balanced manner. The *systematic mapping study* follows a formalized process as well but allows for a broader scope with more general questions when reviewing the topic of interest. This broader review of a larger literature corpus can include the quantity, type, origin, and temporal scope of primary studies as well, and is usually presented on a map.

2.2. Research Protocol

The systematic mapping study for this literature review was conducted in the five-step approach based on Febrero et al. (2014). Figure 1 explains the article search and study selection procedure quantitatively.

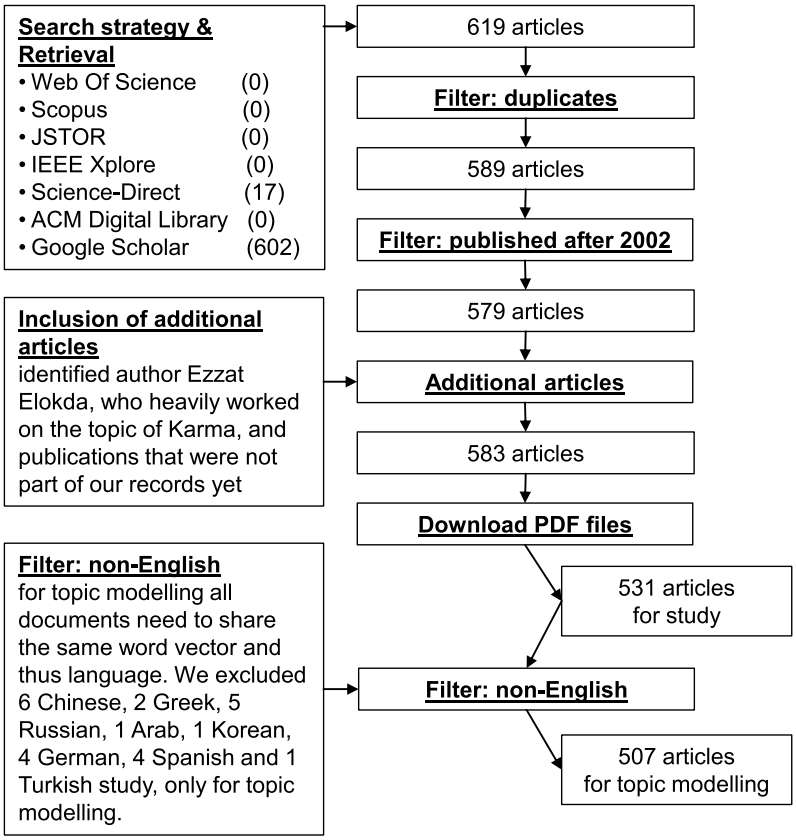


Figure 1. Article search and selection process.

2.2.1. Protocol Planning

Motivation: Starting from the original paper (Vishnumurthy et al. 2003), Karma recognized attention in many different fields and applications. With regard to the number of primary and secondary citations it received and still receives, the interest in Karma is growing. New applications and significant adoptions can be found every year. However, the citing literature is dispersed over time and across disciplines: While at the beginning Karma was a sore subject in the filesharing literature (to overcome free-riding in peer-to-peer networks), it has become more prominent in the block-chain literature (foundational technology for modern cryptocurrencies), and is about to receive significant attention in the game theory and control literature (as a fair and efficient resource allocation mechanism). There is a lack of an interdisciplinary, comprehensive survey on Karma and all its applications yet, that lays the foundation for systematic, future research. Therefore, this study aims to provide a comprehensive, interdisciplinary, systematic mapping study on Karma as a concept in different fields, and especially as a resource allocation mechanism.

Scope: We are interested in understanding the structure of the literature that evolved around the first work on Karma in the filesharing literature Vishnumurthy et al. (2003), in order to better understand how Karma is defined in different fields, and to establish a common, cross-domain language. Moreover, this study focuses on Karma as a resource allocation mechanism and systematically analyzes the differences and similarities of the applications. In addition to that, the study thematizes how game-theoretic formalism can be used to quantitatively analyze the Karma mechanism. Finally, this work aims to elaborate on potential future research for Karma. Therefore, the broader scope of this systematic mapping study can be summarized by the following ten research questions:

1. How did Karma evolve in the literature over time?
2. What is the intellectual field-structure of the Karma citing literature corpus?
3. What is Karma defined as and which relevant terminology exists in these fields?
4. Which concepts as an alternative to Karma exists in these fields?

5. How is Karma different from other resource allocation mechanisms?
6. How is Karma applied as resource allocation mechanism?
7. What are the parameters & options when designing Karma applications?
8. How to model and formally describe the Karma mechanism?
9. What is a rational policy in a Karma game?
10. Which features does the Karma mechanism provide?
11. What are promising future research questions for Karma?

Search strategy: All papers, that cite the original paper on Karma (Vishnumurthy et al. 2003), are searched. For this purpose, the following established, frequently used, international, interdisciplinary, scientific literature databases are queried: Web Of Science, Scopus, JSTOR, IEEE Xplore, Science-Direct, ACM Digital Library, and Google Scholar. The results are manually reviewed to account for duplicate records.[1]

Selection criteria: Any record that cites the original paper in its reference list is included. Any record from the citing literature that was published before 2002 is excluded, as the original paper was published in 2003 itself, and might have been cited as a forthcoming working paper version one year before that.

2.2.2. Literature Retrieval

The original paper was published as a workshop paper at Cornell University *Vishnumurthy, V., Chandrakumar, S., and Sirer, E. G. (2003, June). Karma: A secure economic framework for peer-to-peer resource sharing. In Workshop on Economics of Peer-to-peer Systems (Vol. 35, No. 6).* As it was not published at a conference or journal later on, only Science-Direct (17 hits) and Google Scholar (602 hits) returned records.

2.2.3. Study Selection and Quality Assessment

For each of the records, the title of the publication, the link to the publication's website, the number of citations (according to Google Scholar), and the download link to a PDF (available for 441 records) were captured. Missing download links were manually completed afterward. After manual inspection of the records, duplicates were removed, resulting in 589 unique papers citing the original work. These duplicates occurred due to multiple versions of the same paper (e.g., preprints) indexed in Google Scholar. For each of the records, the following steps were conducted:

(i) download the scientific publication as a PDF document from the download link
(ii) download their bibliography meta-data as a Bibtex file from Google Scholar
(iii) extract the full text from the PDF files into TXT files for further processing, and
(iv) determined how often Karma was mentioned in the papers by counting the term "Karma".

This procedure was possible for 531 papers of the citing literature, the others were not available for download and could not be found anywhere else. The file size of PDF files and the number of characters in the TXT files are used for manual inspection to identify downloaded files that were empty or just abstracts (too short for a publication). Several of the download links from Google Scholar were not working and had to be complemented manually. The procedure was repeated iteratively until we remained with all data for the 531 records. In terms of document quality assessment, this work chooses to include all studies. Similar to the original Karma paper, many citing works were published outside of journals and conferences, for example, on arXiv or as university-intern publications. As a result, there is no such risk of overlooking any further, relevant literature.

2.2.4. Classification and Analysis

The classification and quantitative analyses were conducted by topic modeling using the Latent Dirichlet Allocation algorithm. During text preprocessing all special, not alphanumeric characters, transformed words to lower case were erased, easy and stop words were removed, and Porter's stemming method Antons et al. (2019); Porter (1980) was applied. In a manual, iterative process, the most frequent 1-grams, 2-grams and

3-grams were reviewed, and where appropriate, excluded from the text or combined the n-grams to single words. In total 55 1-grams, 435 2-grams and 51 3-grams were identified. The processing of n-grams was instrumental in improving the topic models and creating meaningful topics, as consecutive terms like "game" and "theory" should be considered as one word. 24 documents were excluded from topic modeling, as these were not in English language, and therefore, did not share the same word vectors (six Chinese, five Russian, four German, four Spanish, two Greek, one Arabic, one Korean, and one Turkish).

Then, the software implementation[2] was used for calculating the LDA models. Around 1338 models were rendered with different hyperparameter combinations. Consistently, for different alpha and beta values, an inherent optimal number of topics of around 30 was identified. After manual inspection of the topics and topic-word-distribution, the topics were aggregated using grounded theorizing, resulting in six distinct and meaningful topics: "behavior", "Game Theory", "Economics", "Filesharing", "Network and Technology", and "Blockchain". The finally selected model was trained based on 503 documents with in total of 5,264,546 words, covering 86,794 different words of vocabulary (entropy of words −7.81), using an initial alpha of 0.07 (after training the alpha of each topic was around 0.35) and beta of 0.01. The final model has a perplexity of 4048.81 and a negative likelihood of −8.31.

2.2.5. Mapping

First, the number of primary and secondary citations over time are analyzed and how often the term "Karma" occurs in each paper of the citing literature corpus. Then, the topic models are used to analyze which fields Karma was applied most over time. Finally, the topic models are used to analyze the similarity of topics and render word clouds to understand the most frequently used words of each topic.

2.3. Topic Modeling with Latent Dirichlet Allocation

Topic modeling is a mathematical approach to studying large datasets, that can be understood as a principal component analysis, which enables the user to find meaningful topics and uncover latent structures in large datasets. While topic modeling was successfully applied to a variety of data including images, population genetics, survey data and social networks, its most prominent application can be found in bibliometric studies when analyzing textual data (Hannigan et al. 2019). One of the most recognized algorithms for topic modeling is Latent Dirichlet Allocation (LDA) (Blei et al. 2003). It assumes that, for a given dataset, there is an inherent, latent, intellectual structure that follows a Dirichlet distribution. In applications with text, LDA inputs a textual corpus matrix, that consists of the word vectors of each document, and outputs two probabilistic matrices, that represent a topic-document-distribution, and a topic-word-distribution. The quality of topic models can be assessed by the two metrics perplexity and negative likelihood (Blei et al. 2003). Prerequisites to LDA are text preprocessing and hyperparameter selection.

During text preprocessing, a text is split into single words, a list of unique single words is determined, and the word vectors represent the number of times the unique words occur in a document. For text preprocessing, it is common to transform all words to lowercase, to remove easy and stop words, to apply Porter's stemming method, and to identify and replace n-grams Antons et al. (2019).

Hyperparameters, such as alpha (how concentrated is the topic-document-distribution) and beta (how concentrated is the topic-word-distribution) of the Dirichlet distribution, and the number of topics expected to be found, must be preset upfront. One common suggestion followed in the literature for the choice of alpha and beta is to choose alpha as the ratio of 50 and the number of topics, and beta as 0.1. The number of topics can either be predefined or considered as inherent to the corpus. In the latter case, it is common to minimize the negative likelihood respectively maximize the perplexity of the models in order to find the optimal number of topics (Griffiths and Steyvers 2004).

For more details on the code for text preprocessing and analysis using Latent Dirichlet Allocation and detailed parameters, the reader is encouraged to revisit this study's implementation and dataset provided on the online GitHub repository: https://github.com/DerKevinRiehl/karma_literature_review accessed on 13 August 2024.

3. Review of the Karma Literature

3.1. The Origins of Karma

The original work *Karma: A secure economic framework for peer-to-peer resource sharing* (Vishnumurthy et al. 2003) provides a secure algorithm and protocol for resource sharing in peer-to-peer networks. The authors were inspired by the religious concept of Karma in Hinduism, where morally good actions will be rewarded and morally bad actions will be punished (Larson 2020). One of the major motivations for the original work was to solve the free-riding problem on peer-to-peer network marketplaces, which the majority of users consume but only a few provide resources. The authors demonstrate that their proposed concept forces participants to achieve parity between resource contribution and consumption and prove Karma's protocol properties such as non-repudiation, certification, and atomicity.

Even though Karma was originally intended for resource sharing in peer-to-peer networks only, it was used as a network protocol for secure, attack-proof information dissemination systems across peer-to-peer networks. Also, it is considered the first decentralized cryptocurrency, based on a proof-of-work minting[3], which is a foundational technology for modern blockchain technologies. Besides, Karma was discussed as an accounting system, and its behavioral implications were discussed as an incentive mechanism. In addition to that, Karma was modeled as a dynamic population game, and discussed as a resource allocation mechanism (Antoniadis et al. 2005; Caldarola et al. 2022; Elokda et al. 2023; Zhao et al. 2009).

3.2. Two Decades of Karma

The analysis of the Karma citing literature reveals, that there are six distinct clusters within the Karma citing literature: "Blockchain", "Network and Technology", "Filesharing", "Economics", "Game Theory", and "behavior" (Figure 2). Figure 3A explains, that "Filesharing" dominated the Karma literature at the beginning, and that beginning from 2015 "Blockchain" started to subjugate. The analysis of topic distance in Figure 3B,C outlines that "Blockchain", "Filesharing" and "Game Theory" stand out (document-distance), and that "behavior" and "Filesharing" (word-distance) differ from the other topics. With regards to the literature share of each topic in Figure 3E, one can see that the largest share (∼30%) of the literature is on "Filesharing", and the second largest share (∼20%) is on "Blockchain".



Figure 2. *Cont.*

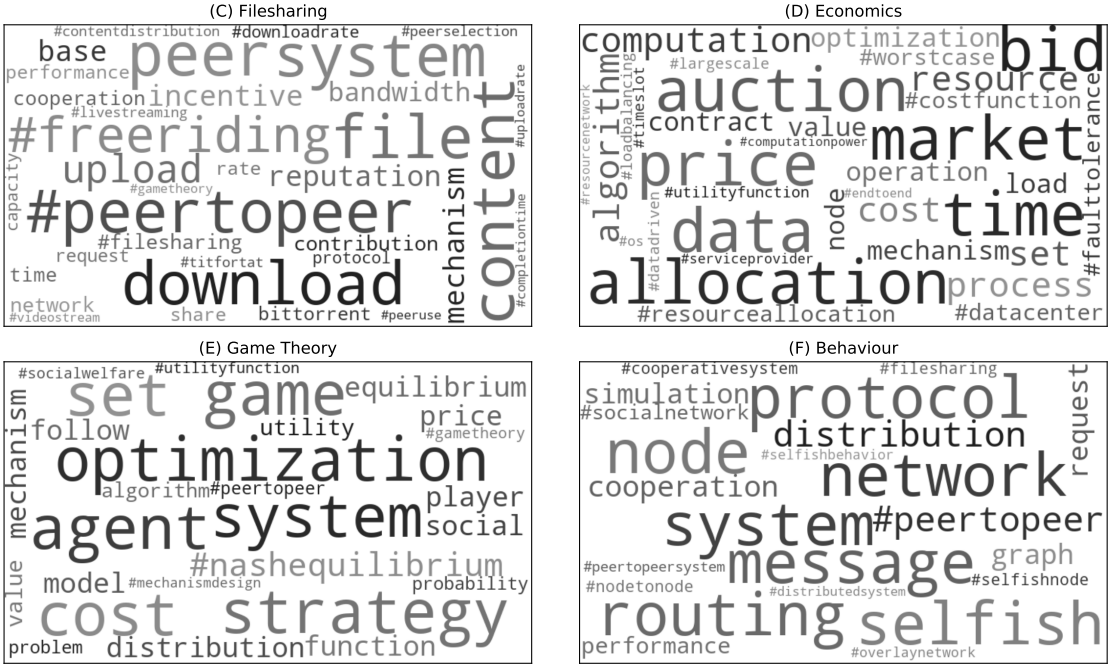


Figure 2. Clusters in the literature corpus. This figure shows word clouds of selected, most frequent words for the six identified topic clusters. The size of words relates to their frequency in the documents.

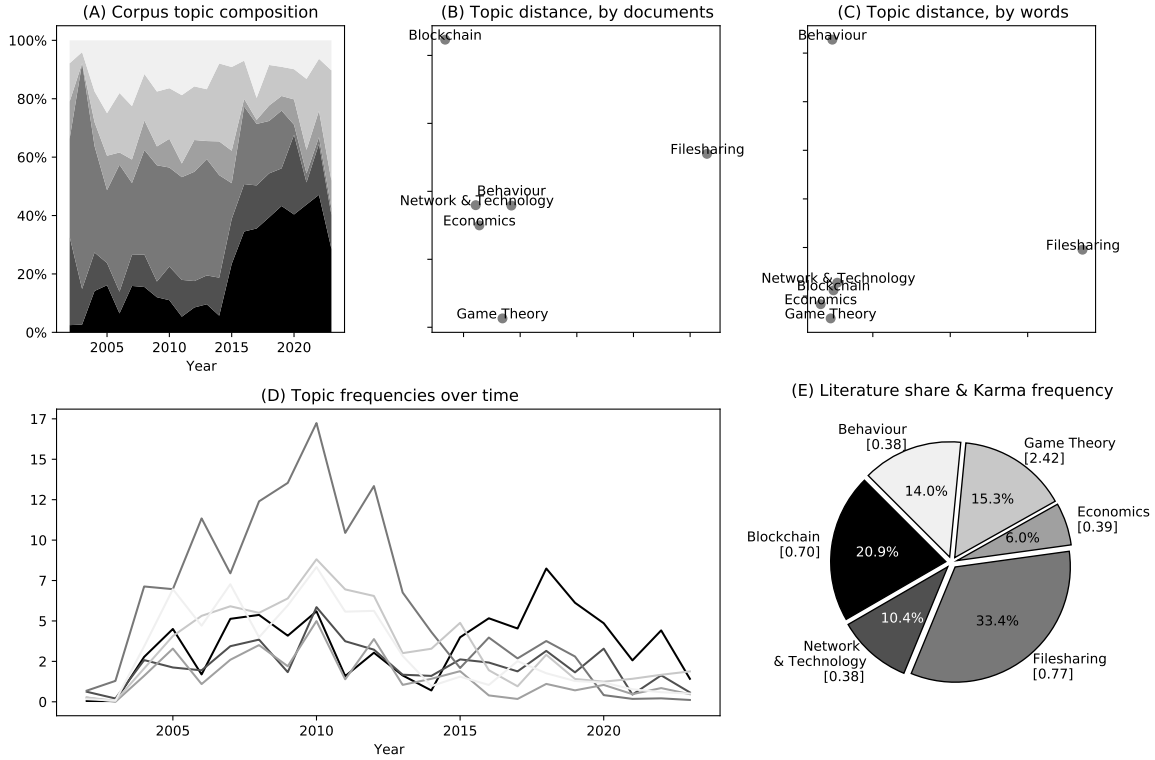


Figure 3. Composition and structure of literature corpus. (**A**) This figure shows the corpus' topic composition. Share of citing literature for a specific year is determined by LDA document-topic matrix probabilities. (**B**,**C**) These charts express similarity of topics depicted as topic distance by documents resp. by words (PCA of LDA's matrices into 2D). (**D**) This figure shows number of primary citations of Karma for each topic and year. (**E**) The pie chart displays share each topic has in the literature on average over observed period of two decades. Number in brackets describes how often "Karma" appears on average in works on this topic.

Over the past two decades, Karma gained momentum as a concept from its first appearance, until its climax in 2012. Figure 4 shows how Karma evolved in the literature over the past two decades. With regards to the primary citations in Figure 4A, it can be observed that around 400 works per year cited the original Karma paper from 2005 to 2010. Afterward, the number declined to around 200 works per year. From 2020, the number of primary citations dropped. To date, Karma has been cited around 583 times. With regards to the secondary citations in Figure 4B, it can be observed that the number of secondary citations increased strongly around 2005 and then later between 2015 and 2020, with around 15,000 secondary citations per year. To date, Karma was secondary cited around 25,000 times. With regards to the cumulative citations divided by years since publication in Figure 4C, it can be seen that the number of average primary citations since publication steadily increased until 2012 to 35 citations per year, and then slightly decreased since then. A similar observation can be made for the average secondary citations since publication.

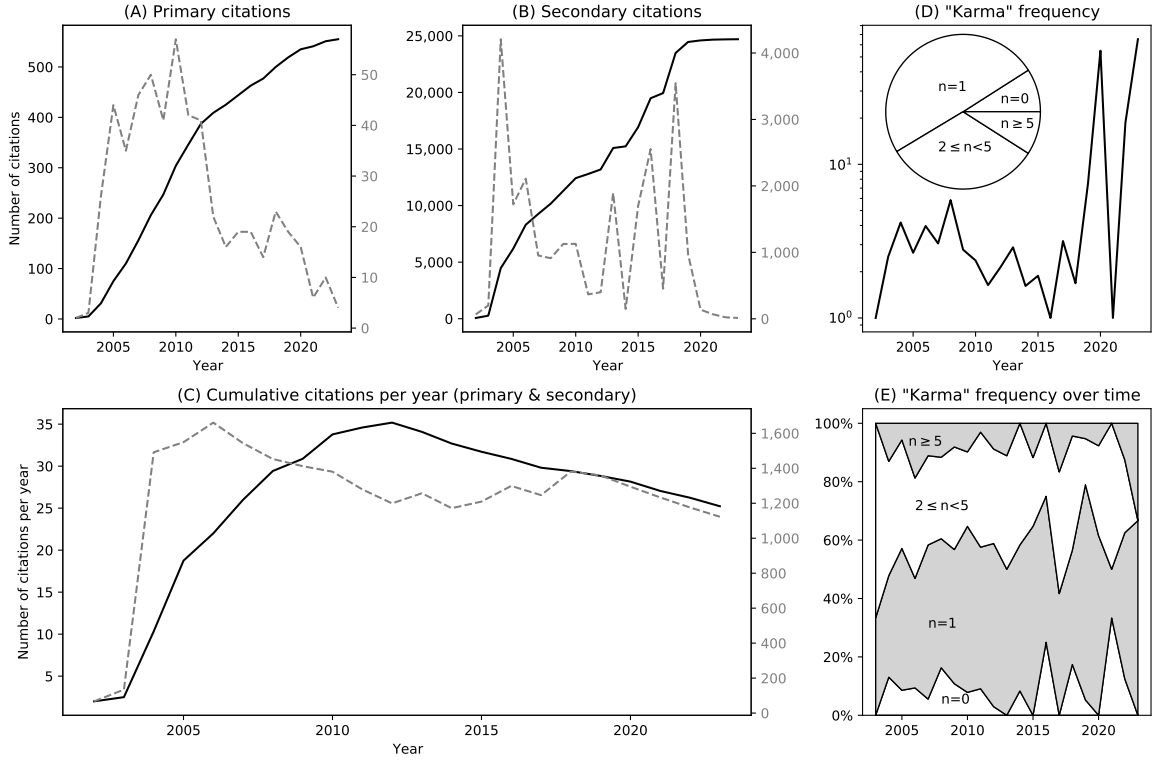


Figure 4. Two decades of Karma. (**A**) This figure shows primary citations (dashed line = citations per year with ordinate on right, black line = cumulative citations with ordinate on left). (**B**) This figure shows secondary citation. (**C**) This diagram shows number of cumulative primary (black) and secondary (dashed) citations divided by the number of years after publication. (**D**,**E**) These charts show number of times "Karma" appears per document, excluding the references. It indicates Karma's role in a paper (only citation or more intensively worked with concept).

An increasing amount of work started to work more deeply with the concept of Karma beginning in 2017. With regards to the number of times the term "Karma" is used in the papers in Figure 4D, we can better understand what drives the number of primary and secondary citations. To start with, it can observed that "Karma" was used as a term in scientific studies around two to three times per document on average until 2017. Afterward, it strongly increased up to 14 times (with an exception in 2021). This development indicates that while "Karma" was just cited as a side note at the beginning, it was recognized and developed further as a concept later on. Therefore, one could argue that interest in the concept of "Karma" increased since 2017, as the citing literature started to work with the

concept more intensively. The pie chart makes it obvious that the peaks in Figure 4D are mainly driven by few publications, as the vast majority (60%) of the documents cited Karma only one to two times. With regards to Figure 4E this can be supported by an increase in the share of publications up to 30% that cite "Karma" more than four times on average per document.

First, Karma was prominent in the "Filesharing" field, then the "Blockchain" field, and now the "Game Theory" field predominantly works with Karma. Figure 3A exhibits the fields that drive the citations of the original Karma paper. One can see that while in the beginning "Filesharing" was predominantly cited, (around 40%) in the first years (2002–2014), there was a shift towards "Blockchain" (around 35%) related parts of the citing literature corpus (beginning from 2014); in the last years (2022–2023) one can see a significant increase in "Game Theory" citations (around 25%). With regards to the absolute number of citations in Figure 3D one can see that the "Filesharing" literature was around two times larger than the "Blockchain" literature, and the emerging "Game Theory" literature is even smaller. Figure 3E (number in brackets) displays how frequently the term Karma was used per document in the different fields. One can see that the Karma frequency as discussed in Figure 4D was mainly driven by the "Game Theory" field, where on average each paper cited the term "Karma" 2.42 times, compared to "Filesharing" (0.77 times) and "Blockchain" (0.70 times).

3.3. Karma modeled as a Game

Karma is described inconsistently in its applications as a resource allocation mechanism. It is described verbally, rather than modeled formally for quantitative analysis. When simulating Karma (e.g., as a multi-agent system), assumptions about the agents' behavior are made many times. In 2019, Karma was modeled with a game theoretical formalism (Elokda et al. 2023), which enabled a more precise, reproducible, quantitative assessment of this novel resource allocation mechanism. The benefit of this formalism is the possibility to predict the behavior of selfish (rational) agents when simulating Karma resource allocation systems.

Karma is described as a repeated, stochastic, dynamic population game. It applies to games that are not played once, but multiple times (repeated). Many aspects of the game are modeled probabilistically (stochastic), i.e., the bidding behavior is modeled as a Markov decision process. The formalism applies to dynamic population games, in order to represent the strategic interplay in large societies of rational (selfish) agents (Elokda et al. 2021).

In the Karma game, there is a population of agents, where each agent

- has a specific amount of Karma
- has a random, time-varying urgency (represents the agent's cost when not obtaining a specific resource)
- has an individual temporal consumption preference type (discount factor, represents the subjective trade-off between consuming now versus later)

Agents are matched randomly every round to compete for a specific resource, by bidding with Karma in auction-like setups. Depending on their urgency, Karma balance, and consumption type, agents must determine an optimal bid to earn the resource when necessary, while accounting for potential future competitions in following rounds. This bidding behavior can be described by a probabilistic distribution called the policy. The optimal policy describes the behavior of rational agents, meaning that no agent can gain by deviating from this policy. Moreover, the population's Karma balance distribution (across urgency, Karma balance, and consumption types) can be described by a probabilistic distribution called the state. Over time, a population of rational agents will converge to a stationary state called the stationary Nash equilibrium. The stationary Nash equilibrium consists of the optimal policy and stationary state distribution is guaranteed to exist for dynamic population games, and can be calculated. The interested reader is highly recommended to review further details in the works of Elokda et al. (2021, 2022, 2023).

4. Karma Resource Allocation and Mechanism Design

4.1. Applications of Karma as a Resource Allocation Mechanism

A growing number of works study and employ Karma as a resource allocation mechanism for prosumer resources. Often, Karma is used for the distribution of resources in peer-to-peer networks, such as cloud computing, telecommunication, road transportation, or social networks, as shown in Figure 5. In the literature field "Filesharing", Karma was applied in virtual, P2P networks, for the allocation of computational resources such as files (Garcia and Hoepman 2004; Vishnumurthy 2008; Vishnumurthy et al. 2003) and computation power (Mitra and Maheswaran 2005; Oliveira et al. 2011). In the literature field "Network and Technology", Karma was applied in telecommunication networks, for mitigating distortion signal interference with other agents (Shen et al. 2014), and sharing of internet access (Buttyán and Hubaux 2001, 2003; Efstathiou 2006; Mastronarde et al. 2015; Xu and van der Schaar 2013). In the literature field "Blockchain", Karma was not applied as a mechanism, as this branch of literature mainly focuses on applications as an accounting system for blockchain technologies such as cryptocurrencies. In the literature field "Game Theory", Karma was applied in road transportation networks, for toll-pricing (Pedroso et al. 2023; van de Sanden 2022), intersection management (Censi et al. 2019; Elokda et al. 2023), and priority lanes Elokda et al. (2022, 2023). In the literature fields "behavior" and "Economics", Karma was applied in social and logistic networks, for the distribution of food donations (Prendergast 2022), babysitting services (Johnson et al. 2014), living-organ donations (Kim et al. 2021; Roth et al. 2004; Sönmez et al. 2020), and vacancies for individuals (Gale and Shapley 1962; Hylland and Zeckhauser 1979). An exhaustive compilation of relevant Karma applications for resource allocation mechanism can be found in Tables A1–A3.

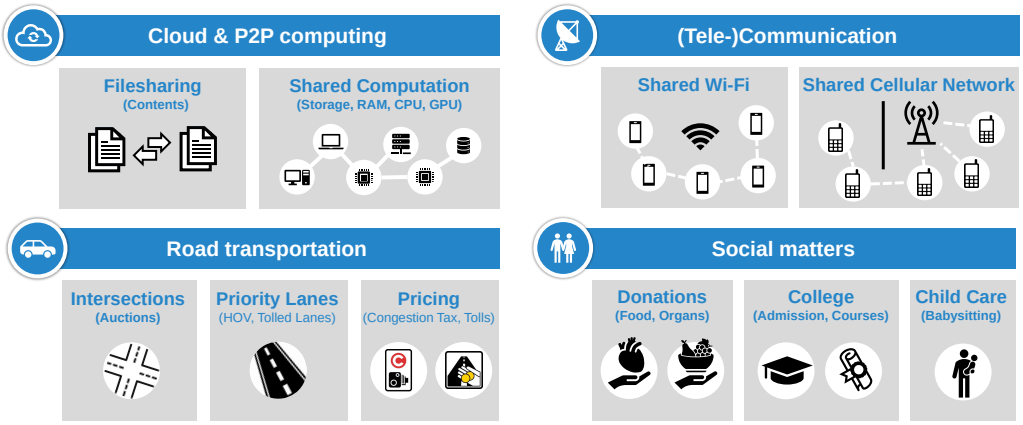


Figure 5. Existing Karma Applications.

4.2. Karma Mechanism Design Framework with Parameters and Options

A systematic comparison of the Karma resource allocation applications was conducted involving agents, resource of interests, the problem that was tried to be solved, source of resource, system and user goal, as well as possible actions of agents, which is shown in Tables A1–A4. Based on this comparison, the similarities and differences of the different applications were summarized in three groups of design parameters: currency, interaction, and transaction. The design parameters are presented in Table 1.

Table 1. Karma mechanism design parameters and options.

Design Parameter	Option
Currency	
Parity	Price, Threshold, Binary
Balance limits	Unlimited, Bounded (upper, lower)
Amount control	Constant (per capita), Uncontrolled, Expiry, System
Initialization	Equal endowment, Weighted endowment, Random endowment, None
Redistribution	Property tax, Payment tax, Lottery, None
Interaction	
Price control	Auction, Centrally defined, None
Price limits	Only positive, Binary, None
Resource provision	By agent(s), By system
Resource allocation	Auction winner, System decision, Provider decision
Counter-party	N agents, One agent, System
Peer selection	Market, neighborhood, Randomly assigned, Active selection
Decision-making	Free
Urgency process	Homogeneous, Heterogeneous
Temporal preference	Homogeneous, Heterogeneous
Transaction	
Payment amount	Bid, Peer's bid, Difference in bids, System Order, Fixed, Nothing
Payment receiver	Resource provider, System, Equally across population, Weighted across population
Karma gain	Resource provision, Resource consumption
Karma loose	Resource consumption, Expiration, Rule-violation

As it turned out, in many of the Karma-applying works a major design complexity is choosing the right amount of Karma currency in circulation (Johnson et al. 2014; Pedroso et al. 2023; Shen et al. 2014; van de Sanden 2022). If there are too few currency units, there will be hoarding to save the scarce currency for very urgent situations to consume; if there are too many currency units, the value of a single value is not sufficient anymore to stimulate the provision of resources. In the case of a time-variant resource supply, a dedicated amount of control becomes necessary.

In the following, each of the design parameter groups is discussed in detail. For exemplary references of applications that employ a specific design parameter option, a listing in Table A5 is provided.

The **currency parameters** include parity, balance limits, amount control, initialization, and redistribution:

- The *parity* represents the relationship between Karma and the resource. The parity could be a price, meaning that resources can be traded for different amounts of Karma. This can be useful in case of non-homogeneous resources, e.g., a large file can be exchanged against three small files. The parity could also be binary, meaning that one resource can be traded for exactly one unit of Karma. This can be useful for homogeneous, atomic resources, e.g., one evening of babysitting service. The parity could also be a threshold, meaning that an agent needs a certain amount of Karma to be eligible to consume resources.
- The *balance limits* represent the limitations of Karma ownership. Either, agents could have unlimited amounts of Karma, or there could be restrictions towards upper bounds to avoid hoarding. Depending on the resource allocation mechanism, the absence of lower bounds could also enable an agent to have Karma debts to a certain amount.
- The *amount control* represents the monetary control mechanism to control the total amount of Karma circulating in the system. Either it could be controlled by the system itself, in order to keep the amount of Karma per capita at specific levels. It could also just be constant or not controlled at all. Besides, Karma points could also expire or depreciate.

- The *initialization* represents how agents are initially provisioned with Karma. This could mean at the beginning of the establishment of a Karma mechanism, or dynamically for new joining agents. This could either happen by an equal, or random initial endowment, or not at all, meaning that agents need to provide some time before they can consume. Prendergast (2022) even used a weighted initial endowment according to the central coordinators' perception of need.
- The *redistribution* represents schemes of how Karma is redistributed across agents. It could be, that after each period, Karma is distributed via taxation of property. It could also be redistributed by taxation of payments, via a lottery, or there could be no redistribution at all.

The **interaction parameters** include price control, price limits, resource provision, resource allocation, counter-party, peer selection, decision-making, urgency process, and temporal preference:

- The *price control* represents how prices for resources are determined. Prices could be determined by market mechanisms such as auctions, where forms of bidding processes take place with varying degrees of information transparency. Besides, prices could be determined by a central coordinating authority (the system), or not determined at all (in the case of binary parity).
- The *price limits* represent the limitations of resource prices. Prices could be not limited at all, meaning also negative prices could be possible leading to earning Karma through consumption (e.g., goods with negative utilities). Prices could also only be positive, defined by rational behavior, or price limits could be fixed (in the case of binary parity).
- The *resource provision* represents who is the resource provider. Either agents could provide resources, or the network (system) itself.
- The *resource allocation* represents how a decision is made about whom to provide the resource to. Depending on the price control, it could be the highest or the second highest bidder who receives the resource; it could also be a trading and exchange system that executes orders such as for double actions. In cases, where not a large number of agents, but only a pair of two agents interact, the resource provider could assess if the bid is high enough the effort. Besides, if the resource is provided by a central system or network, it could always be provided to the agent, in case it accepts the system defined price.
- The *counter-party* represents with whom an agent interacts. It could be that the agent interacts with (all) other agents in case of a market (auction). Besides, it could also be that the agent just interacts with exactly one other agent, or with no other agent but the system itself.
- The *peer selection* represents how agents find their peers for an interaction. It could be that agents find (all) other peers through the market, so they do not decide actively for peers. Similarly, the neighborhood or a recommending/guidance system could provide a subset of the market to compete with. It could also be, that agents are randomly assigned through each other, e.g., meeting at an intersection. And finally, it could be actively selecting peers.
- The *decision-making* represents if agents are free to make their decisions. It is important to emphasize, that in the Karma mechanism, the buyers and sellers are always free to make their decisions (neglecting their urgency and needs).
- The *urgency process* represents how the urgency of agents emerges over time. It could be that all agents share a similar (homogeneous) or a different (heterogeneous) urgency process, with similar or different probabilities for different levels of need. Moreover, it could be that the urgency at a later point in time depends on previous resource allocation, e.g., starvation or dehydration.
- The *temporal preference* represents how agents prefer present over future consumption. It could be that all agents share a similar temporal consumption preference (homogeneous), or that they differ (heterogeneous).

The **transaction parameters** include payment amount, payment receiver, Karma gain, and Karma loss:

- The *payment amount* represents what a buyer (agent) needs to pay in case it obtains the resource allocated. Depending on the price control and other design parameters, there are many payment rules possible. The buyer could pay the bid, the bid of the peer, the difference between its and its peer's bid, a fixed price (in case of binary parity), an ordered amount by the system, or even nothing.
- The *payment receiver* represents who receives the Karma paid by the buying agent. It could be, that the resource-providing agent receives the payment, or that the payment is equally distributed across the population of agents, or weighted distributed according to how much Karma the population has, or to the system.
- The *Karma gain* represents how agents can earn their Karma units. Agents could earn Karma by providing resources; in case of negative prices, it could also happen by consumption.
- The *Karma loss* represents how agents can lose their Karma units. Agents could lose Karma by resource consumption or expiry. Besides, agents could also lose Karma by untrustworthy, rule-violating behavior.

4.3. Karma Mechanism Design at the Example of Wi-Fi Sharing

To better illustrate the usage of Karma with its various parameters and options, let us discuss the resource allocation application of a shared Wi-Fi system based on Efstathiou (2006). The idea behind shared Wi-Fi is, that while you are at home, people passing by your home, could use your Wi-Fi hotspot from outside while passing by. When you are outside, you can use the hotspot of others. The more people participate and share their Wi-Fi, the higher the network coverage, and value for the overall system. In the following, possible design parameter option choices for this example are discussed.

Currency: The *parity* could be a price, meaning that for a certain amount of data consumption (e.g., in megabytes) a certain price needs to be paid, which is defined by the owner of that specific hotspot. It could also be that if you are a member of the system, and provided a certain amount of Wi-Fi sharing yourself (and thus reached a membership contribution threshold), you are free to use as much as you want from the others. Or it could be, that you can only assume as much data (e.g., in megabyte) as you shared with others before, and not more. The *balance limit* refers to how much Karma you can collect. It could be, that you can only earn a limited, maximum amount of Karma, and not more. Or it could be completely unlimited. In order to guarantee a successful running of the system, initially there must be individuals that have a certain amount of Karma, so that other individuals can start earning Karma by providing the shared Wi-Fi to them. The *initialization* could be equal, meaning every individual starts with a certain budget, or it could be randomly distributed. In case there is a specific reason to advantage certain groups of people, an initial endowment could also follow certain weights each individual has according to their group (e.g., students obtain more initial Karma than seniors). Finally, it could be, that there is no initialization with Karma. This would mean the Karma market for Wi-Fi would be illiquid, as nobody owns Karma to consume, and nobody can earn Karma by providing as nobody can afford to consume. This could then be solved by a certain amount of control or redistribution activities. The *amount control* could be constant, meaning that the total amount of Karma in circulation is fixed, or adjusted to a fixed per capita amount by the system. This could make sense if the number of individuals in the Wi-Fi sharing changes dynamically, as the Wi-Fi sharing platform gains popularity with more and more users. It could also be that Karma points can expire after some time, to make sure that users that contributed a lot but never consumed do not cause illiquidity of the Karma market. Finally, a central system actor could also dynamically control the amount of Karma to control the liquidity of the market to achieve certain goals (e.g., no internet during night rest). The *redistribution* could be another measure in addition to the amount of control to address illiquidity in the case of providers that do not consume equally.

Redistribution could happen via a property tax, e.g., every day you lose 5% of your Karma balance, which is redistributed across the population. Or there could be taxation of each transaction, e.g., for each payment during consumption, not only does the provider receive Karma for providing, but a small share is taken by the system and redistributed equally to everyone. It could also happen via a lottery system, e.g., two users are randomly chosen, and then there is a random amount of Karma that is deducted from one and credited to the other one.

Interaction: The *price control* (in case a price parity is chosen) could happen in three different ways. Either, prices are centrally defined (e.g., the system defines an amount of Karma per megabyte, in concordance with amount control), or via auctions (e.g., provider and consumer negotiate based on price preferences). The prices could then be constrained by *price limits*, to make sure that a certain stability of market prices is guaranteed, e.g., it makes sense that prices are positive (e.g., you spent Karma when using a Wi-Fi hotspot). Moreover, in the case of binary parity, prices would always equal 1 (every megabyte consumed requires a megabyte provided to others). In this example, *resources provision* is conducted by the other agents, as they share their Wi-Fi hotspots with you. However, a system could make a final decision on whether the resource is provided or not, in case a central agent aims to systematically exclude malicious users. The *resource allocation* describes who exactly receives the provided resource. In the context of this example, let us imagine that there are two users who would like to use the hotspot at the same time, but the provider of the hotspot restricts the provision to only one foreign user at a time, to make sure the internet quality for himself is guaranteed. Then, there could be an auction between the two contestants, and the winner of the auction (e.g., a first-price auction) would obtain the resource allocated (receive the right for Wi-Fi consumption). Or it could be that a system decides based on some specific rules who receives the resource, or it could be that the provider has a predefined decision rule, e.g., based on previous good experiences consuming a certain contestant's Wi-Fi he has preferences over one of the two contestants. The *counter party* in this context would be another user that while passing by your house would like to use your Wi-Fi hotspot. In other examples, it could be possible that there are always multiple contestants as counter-parties that one must compete for, or it could be that the system is the actual counter-party, in case a system provides a resource (e.g., a food donation), and not another user. The *peer selection* describes how providers and consumers/counterparties find each other. It could be a random process, or it could be that users of a certain neighborhood are more likely to interact when compared to more distant users. It could also be that a consumer passes by multiple houses and chooses the shared Wi-Fi hotspot with the lowest price (active selection). Finally, in other examples, it could make sense that peer selection happens on a market (in resource allocation contexts that are not restricted to physical distances, e.g., file-sharing platforms online). The *decision making* process of users of the Wi-Fi sharing system is free, based on their *urgency process* and *temporal preference* only. Let us imagine that the sharing has a price parity. Now, a potential consumer must trade-off, depending on his urgency, if he is willing to spend his Karma now, because he is urgent now, or rather save his Karma for a later situation when he is more urgent. Depending on his preferences, he will weigh potential future needs more than current needs. One could assume that every user has similar temporal preferences (homogeneous) when modeling and simulating such a system, but most probably users will differ in their preferences (heterogeneous) which complicates the simulation of such a system. The urgency of a user is assumed to be a random process, e.g., every 10th day it is urgently important to use the internet outside, while the other days it is not that urgent. Again, one could assume equal or different urgency processes amongst the users.

Transaction: The *payment amount* defines how much a consumer needs to pay. In the case of auctions, it could be that the own bid (first price auction), the peer's bid (second price auction), or a difference between the two highest bids must be paid. It could also be, that the system defines a price, or that the price is fixed, e.g., due to binary parity. It could also be, in terms of a threshold parity, that nothing needs to be paid, as long as certain

minimal contributions are met by the user. The *payment receiver* defines who receives the payment of the consumer. Most obviously, the provider of the resource could be the receiver of the payment, otherwise, there would be no incentive to provide internet to others. However, in the presence of redistribution activities, it could be possible that the payment is equally distributed across the whole population. In case the system is providing the resource (and not other users), the system would be the payment receiver. In this example, *Karma gain* works through providing to others, and *Karma loose* works through consuming the internet from others. However, in the case of resources with a negative utility/value (e.g., a delay that you are willing to take in order to let someone else pass), one could argue that Karma is gained by consuming a resource (experiencing a delay) and vice versa for the Karma loss case. In the Wi-Fi sharing example, Karma could also be lost by rule-violating behavior or expiration, e.g., when minimum threshold contributions are not met, or illegal content is downloaded via the internet of someone else's hotspot.

4.4. Other Applications of Karma

Karma was not only applied as a resource allocation mechanism, but also in a variety of many other applications and contexts. Table A6 summarizes the application fields of Karma in the different literature fields. Appendix B of the appendix summarizes relevant terminologies to describe these applications, as well as the appendix provides alternatives to Karma for each of these application fields.

5. Future Research Directions

Based on the systematic mapping study, six groups of promising future research directions were identified: (i) novel applications, (ii) in-depth analysis of the Karma mechanism, (iii) effect of Karma agent penetration on systems, (iv) an economic, comparative analysis of Karma with monetary market mechanisms, (v) social experiments and empirical observations from Karma economies, and (vi) interdisciplinary research on accounting and blockchain integration.

Applications: Karma is a resource allocation mechanism, that could be used in many further applications. There is great potential, especially in the following three application areas (Figure 6): industry, people, and government. These application areas are especially suitable for Karma, as they are concerned with socially- and fairness-relevant resource distribution conflicts, and could be modeled as prosumer resource problems. *Industry* includes possible applications at the intersection of technological and corporate agents in energy, telecommunication, computation, logistics and transportation, and production and supply-chain applications. *People* includes possible applications in the distribution of socially important and fairness-relevant resources such as education, housing, mobility and healthcare. *Government* includes possible applications in interactions between authorities and the population, but also between different states or sub-regions, such as regional development, executive operations, and emergency aid.

In-depth analysis of the Karma mechanism: One could analyze the following points in more detail: (i) the robustness to population heterogeneity, (ii) fairness and efficiency, (iii) the online learning and application of (sub-)optimal policies by agents, and (iv) the out-of-equilibrium behavior. Besides the theoretical computations of the optimal, selfish strategy of agents, it would be interesting to assess whether (human) agents are actually able to learn the optimal strategy themselves and to act accordingly. Moreover, how would non-optimal behavior (policies) affect the efficiency and fairness aspect that Karma proposes as value? In terms of the aspect of fairness, it would be interesting to analyze the effect of the Karma mechanism on fairness in depth or at certain aggregation levels. In addition to that, extensive works on the interplay and relationship between fairness and efficiency are promising. As Elokda et al. (2023) argue, the first analysis on the robustness of the Karma mechanism to population heterogeneity was conducted; however, more work needs to be conducted in this aspect of the Karma mechanism as well.

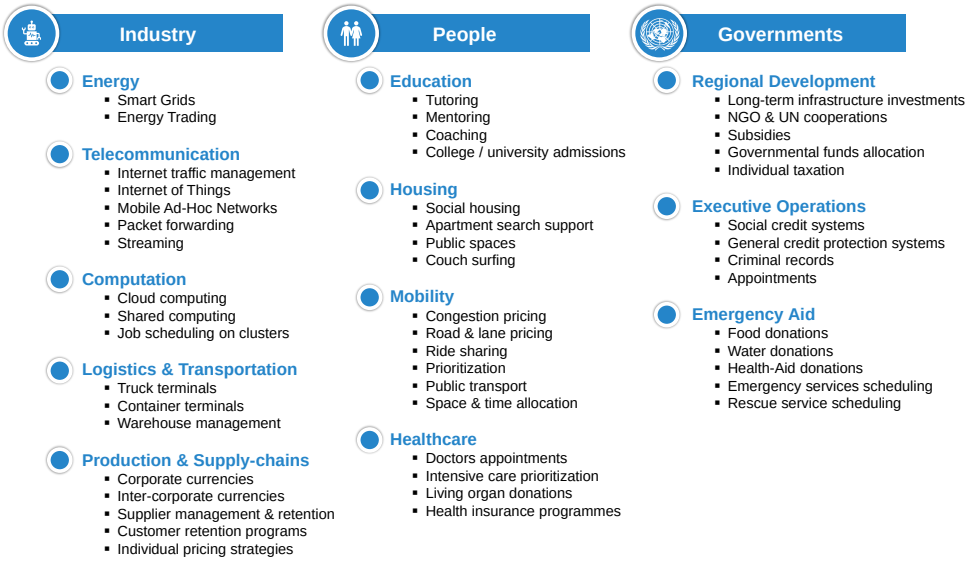


Figure 6. Vision for Karma Applications.

Effect of Karma agent penetration on systems: For many real-world applications it is reasonable to assume, that during the introduction of Karma-based systems, there will be transition periods where populations of Karma-using and not-Karma-using agents will coexist. The effects of Karma on fairness and efficiency for mixed-population systems at different penetration rates could be interesting to study.

An economic, comparative analysis of Karma with monetary market mechanisms: In addition to that, it would be interesting to systematically compare and analyze Karma as a non-monetary mechanism with monetary mechanisms. Karma could be used to comparatively measure the efficiency losses of translating utilities to money in monetary markets. Besides, it could be interesting to quantify boundaries for market conditions in which non-monetary Karma markets outperform monetary markets.

Social experiments and empirical observations from Karma economies: Even though the modeling of Karma as a game allows for the prediction of rational user behavior, previous observations in the field of behavioral economics revealed, that humans tend to act not fully-rationally, as decision-making processes are affected by cognitive biases. Empirical investigations on actual, human behavior in real-world, social experiments on Karma economies could explore how close human behavior is to optimal (rational) behavior. Furthermore, the implications of sub-optimal behavior on the fairness, efficiency, and robustness of the Karma mechanism are relevant to the study.

Interdisciplinary research on accounting and blockchain integration: For a successful, real-world implementation of a Karma economy to a resource-allocating process, an accepted and forgery-proof accounting system on the contributions of individuals and their Karma transactions is vital for the functioning of the system. The employment of modern, distributed ledger technologies such as blockchain, smart contracts and cryptocurrencies could be promising for creating such an accounting system. Technological limitations such as the number of users, transactions, speed, energy consumption, and cyber-security need to be taken into account.

6. Concluding Remarks

Karma is a non-monetary, artificial currency for resource allocation. It can only be gained by producing and only be lost by consuming a specific resource. Karma is Pareto-efficient, fairness-enhancing, near incentive-compatible, robust towards population heterogeneity, and can also lead to a decrease in resource scarcity in peer-to-peer markets.

This study set out to provide an exhaustive literature review on the Karma mechanism for resource allocation and to connect Karma with the context of its literature. A systematic mapping study and topic modeling was conducted, finding that Karma originated as a

concept in the filesharing literature, that gained momentum in six different disciplines. Karma was applied as a resource allocation mechanism in various applications, which have been systematically compared. As a result, this study provided an instrumental framework with design parameters and options, to enable more systematic application of the Karma mechanism. Finally, the results from the review were used to recommend future research directions for Karma.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/economies12080211/s1.

Author Contributions: K.R.: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing—Original Draft, Visualization, Project administration. A.K.: Writing—Review and Editing, Validation. M.A.M.: Writing—Review and Editing, Validation, Supervision. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The source codes, literature corpus (list of publications considered for this review) and computational results of the Latent Dirichlet Allocation topic modeling can be found in the online GitHub repository: https://github.com/DerKevinRiehl/karma_literature_review accessed on 13 August 2024.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Tables

Table A1. Applications of Karma as a network resource allocation mechanism (1/2).

Ref.	Context Summary	Description and Problem
	P2P and Cloud Networks	
Garcia and Hoepman (2004); Vishnumurthy (2008); Vishnumurthy et al. (2003)	**Title:** Resource sharing in peer-to-peer networks **Examples:** Filesharing like GnuTella, BitTorrent, Napster, eDonkey2000 **Agent:** User/participant **Resource:** Resources provided by other agents (such as files)	Agents can share resources with other agents by consuming (=downloading) and providing (=uploading). **Problem:** Lots of users just consume, but do not contribute resources.
Oliveira et al. (2011)	**Title:** P2P network of (home) computers **Examples:** BOINC, SETI@home, GINGER **Agent:** Computing machine **Resource:** Computation cycles (to calculate a certain result from executing a computer program)	Agents can offer their idle time to execute jobs (depending on requirements such as OS, available software, max. RAM and CPU…) and execute jobs on other machines when needed. **Problem:** The decision where one or multiple jobs are executed, and how to prioritize jobs in case there are too many jobs and too few idle machines (that fulfill the requirements) at the same time.
Mitra and Maheswaran (2005)	**Title:** P2P public-resource management of computing utilities in Galaxy Network **Examples:** BOINC, SETI@home **Agent:** computing machines, in the roles of resource participant (RP) and resource broker (RB) **Resource:** Computation cycles (capacity shares)	Computing machines, such as local research clusters, need to execute computing jobs on demand, for the rest of the time they are idle. Being connected to the proposed Galaxy network enables them to speed up their own jobs by using the idle times of other agents, but also requires them to offer their idle time to others. **Problem:** Computing machines leave the Galaxy network when they do not see the benefit of sharing their resources during idle times.

Table A1. *Cont.*

Ref.	Context Summary	Description and Problem
	Telecommunication Networks	
Shen et al. (2014)	**Title:** Distributed small cell network for mobile communication **Examples:** 5G, LTE **Agent:** User equipment (mobile cell phone, UE) **Resource:** "Silence of others", others not being connected to neighboring small cells in case one agent is at the intersection of two cells for a specific amount of time	Agents can connect to one small cell, then call, and move around; when they leave one cell they just enter the next one and can use the system again. **Problem:** Downlink inter-cell interference problem = when the agent is at the intersection of two cells, and experiences interference with an active neighboring cell; therefore, its signal-to-noise ratio SNR drops significantly and causes an outage in the call; turning off the neighboring cell to mitigate the problem can yet cause the outage for other agents that could be in that cell at that time.
Efstathiou (2006)	**Title:** Shared wireless local area network **Examples:** HotSpot, Connectify **Agent:** A mobile user in need of internet, who is member of the system **Resource:** WLAN access and use	WLANs are increasingly installed everywhere and usually cover greater areas than intended by installers. Mobile users that are members, can use WLANs offered by other members, instead of mobile data to have higher speed and less mobile data consumption. **Problem:** Members can not always consume, they also need to provide for others in order for the system to work.
Buttyán and Hubaux (2001, 2003); Mastronarde et al. (2015); Xu and van der Schaar (2013)	**Title:** Mobile (ad-hoc), Wireless Relay Networks **Examples:** LTE, 5G **Agent:** A mobile user in need of transmission of a package but with no direct signal to a base station (such as from a cellular network) **Resource:** Relay transmission service	Agents sometimes need to use the internet on demand while being mobile, but due to their movement sometimes have no direct connection to a mobile internet base station. However, other agents can share internet access by forwarding (transceiving) packages forming an indirect signal path and making the internet more accessible. This forwarding by other agents is called relay transmission. **Problem:** Offering relay transmission for others is causing agents costs, such as battery drain and reduction in bandwidth.
	Road Transportation Networks	
Pedroso et al. (2023); van de Sanden (2022)	**Title:** Toll-pricing in mesoscopic transportation networks of two nodes and n arcs (parallel-arc network) **Examples:** three possible ways of travel from A to B but have different travel times such as different modalities like car, bike, public transport **Agent:** Commuter **Resource:** Capacities of different ways of traveling	Commuters can travel (or stay at home) using different ways of transportation that offer different comfort. For each way of transportation, they need to pay a price in Karma points. The prices are defined by a central controller that learns data-driven how to global-optimally design prices. **Problem:** Commuters can travel (or stay at home) using different ways of transportation that offer a different comfort. For each way of transportation, they need to pay a price in Karma points. The prices are defined by a central controller that learns data-driven how to global-optimally design prices.
Censi et al. (2019); Elokda et al. (2023)	**Title:** Intersection management through coordination mechanism in road networks **Examples:** road intersection **Agent:** Vehicle **Resource:** The right to pass the intersection first	Vehicles drive in a road network and pass intersections. In case two vehicles meet at an intersection at the same time, they need to coordinate themselves on which vehicle can pass first. Vehicles have different urgencies depending on external factors. **Problem:** How to coordinate which vehicle can pass first.
Elokda et al. (2023, 2022)	**Title:** Traffic congestion management with priority lanes for rush hours **Examples:** roads to enter cities, and shared by lots of commuters with similar origins and destinations **Agent:** Driving commuter **Resource:** The usage of priority lanes	Commuters use a road with two lanes. On a daily base, commuters can either use a free lane, which is usually slower due to congestion or use a priority lane and pay a certain fee to travel faster. **Problem:** The morning commute problem, which describes the phenomenon that many commuters share similar origins, destinations and preferred times of arrival, which can cause traffic congestion on roads with limited capacity (bottleneck).

Table A2. Applications of Karma as a network resource allocation mechanism (2/2).

Ref.	Context Summary	Description and Problem
	Social Networks	
Prendergast (2022)	**Title:** Donation allocation across a network of food banks **Examples:** FeedAmerica, Tafel **Agent:** Food bank **Resource:** Food donations, truckloads	FoodBanks distribute food to the poor in society and have many different sources of donations. One major supplier of food banks in the USA is FeedAmerica. FeedAmerica is a large donation-collecting platform with warehouses and logistics, that forwards the donations to foodbanks. Foodbanks use an auction mechanism to bid for truckloads depending on the need and type of truckload. It is also possible that food banks donate food to FeedAmerica which has an oversupply of stock. **Problem:** Before FeedAmerica introduced the auction system, resource allocation was conducted in a centrally planned manner; however, the dynamics of the needs of single food banks, what food banks had on stock locally, and which other sources food banks had available, were impossible to be taken into account.
Johnson et al. (2014)	**Title:** Babysitting Co-Op of the Capitol Hill area in Washington on a network of 150 married couples **Examples:** Capitol Hill **Agent:** Married couple with baby **Resource:** Babysitting service for one evening	Couples with a baby need babysitting services from time to time. They can pay a scrip to another couple to babysit for them, respectively earn a scrip for babysitting another couple's baby for one evening. **Problem:** Find a babysitter when necessary.
Kim et al. (2021); Roth et al. (2004); Sönmez et al. (2020)	**Title:** Living-organ donation allocation between incompatible donor-patient pairs **Examples:** KidneyExchange **Agent:** Incompatible, living donor-patient pairs **Resource:** Patient-compatible organ donation	Living-organ donations are donations of organs from a healthy individual to a person (usually a friend or family). Usually, healthy individuals are just ready to donate organs to a person they know and care about. Unfortunately, there are many medical incompatibilities in donating organs. However, patients can exchange the offering of their friends to donate their organ to another, compatible patient, and in return receive the top position on the waiting list for cadaver donations (or the living donation from another suitable couple) **Problem:** There are too few available organ donations (both living and cadaver). The living-organ donations could complement the number of cadaver donations, but the readiness of living-organ donations is usually just for relatives, friends, and family. Medical incompatibilities of organs impede living-organ donations.
Gale and Shapley (1962); Hylland and Zeckhauser (1979)	**Title:** Individuals obtaining admission to positions **Examples:** College admissions, job offers, PromNight assignment, village marriage problem **Agent:** Individual with admission **Resource:** (Individually) preferred positions	N individuals need to be assigned to N positions. Individuals have a preference over which positions they prefer. Individuals obtain positions, but before accepting them, they can exchange them with other individuals first. This exchange can be repeated several times. Depending on the model, it can also be not the position itself, but the place on a waiting list or the probability to obtain a position that can be exchanged. **Problem:** The preferences of individuals are usually unknown to a central assignment authority. Even if they are known, the assignment can become computationally expensive and complicated.

Table A3. Resource source, goals and actions in Karma applications.

Ref.	Src.	System Goal	Agent Goal	Agent Actions
		P2P and Cloud Networks		
Garcia and Hoepman (2004); Vishnumurthy (2008); Vishnumurthy et al. (2003)	P	Agents have a great user experience and lots of available content on demand relevant to them	Consume as many resources as necessary when desired	- Provide resources - Consume resources
Oliveira et al. (2011)	P	Agents have a great user experience and have their jobs executed as fast as possible when they need it	Get computation jobs executed as fast as possible when necessary	- Order the execution of computation jobs on others machines - Offer idle time to execute computation jobs of others

Table A3. *Cont.*

Ref.	Src.	System Goal	Agent Goal	Agent Actions
Mitra and Maheswaran (2005)	P	- Agents speedup is as high as possible (speedup is the ratio of time executing jobs on demand when being part of the system divided by not being part of the system) - Computing machines should be continuously connected as long as possible (without interruption)	Have highest execution speed of jobs on demand	- Being connected to the network - Not being connected to the network
Telecommunication Networks				
Shen et al. (2014)	N	Minimize the network outage probability (outage is when an agent wants to call but cannot)	Have highest call quality when calling	- Turn of connection to small cell (for a certain period of time), be silent, to not disturb others with their signal - Have an active connection to a small cell
Efstathiou (2006)	P	Network coverage (members can consume WLAN connections when they are mobile and thus experience better internet access)	Have access to as much WLAN as possible when being mobile	- Provide WLAN to other members (when at home) - Consume WLAN from other members (when mobile)
Buttyán and Hubaux (2001, 2003); Mastronarde et al. (2015); Xu and van der Schaar (2013)	P	The success rate of relay transmissions on demand	Have highest availability of mobile internet when needed (either through a direct connection to mobile internet base station or through relay transmission)	- Request relay transmission from other agents on demand - Offer relay transmissions to other agents on demand
Road Transportation Networks				
Pedroso et al. (2023); van de Sanden (2022)	N	Optimal mesoscopic flow (can be aggregated perceived discomfort of all commuters, could also include other goals such as minimizing emissions)	Minimize personal discomfort traveling on a specific way at a specific time (discomfort can be seen in terms of speed respectively how many others use the same way)	- Stay at home - Choose one of the many possible ways of travel and pay a price for it defined by central operator (price represents Karma points, can also be negative meaning receiving Karma points)
Censi et al. (2019); Elokda et al. (2023)	N	Minimize inefficiency (average of all vehicle costs)	Minimize personal costs while traveling (costs mean the level of urgency when the agent needs to let pass and 0 otherwise)	- Pass intersection first - Let other agents pass first
Elokda et al. (2023, 2022)	N	Minimize inefficiency (average of all vehicle costs)	Minimize personal costs (the travel time in context to the urgency at that day)	- Use the normal lane (travel slow) - Use the priority lane (travel faster, pay fee)
Social Networks				
Prendergast (2022)	P	- Maximize volume of allocated donations - Guarantee the provision of all foodbanks to a minimum	- Guarantee the provision of goods for the poor - Maximize the volume of donations used (did not expire)	- Win auction (receive a truckload of specific food, pay bid) - Loose auction (receive bids of the winner) - Sell left-over food (that would be broken otherwise)
Johnson et al. (2014)	P	Maximize the number of available babysitters	Have a baby sitter available when necessary	- Use a babysitting service (pay scrip) - Offer a babysitting service (receive a scrip)
Kim et al. (2021); Roth et al. (2004); Sönmez et al. (2020)	P	Maximize the number of available donations	Minimize the waiting time (to obtain a patient-compatible organ donation)	- Exchange living-organ donation (to another, compatible patient, receive the right to be on priority list or to obtain compatible organ from other pair in return)
Gale and Shapley (1962); Hylland and Zeckhauser (1979)	N	Maximize overall satisfaction with assignment (maximize average satisfaction)	Get the highest preferred position	- Stay with position (already have) - Exchange position (with another individual)

Column "Src." describes the source of resources, where P stands for resource generation by participants and N stands for resource inherence by the network.

Table A4. Comparison of Karma applications.

	Currency					Interaction							Transaction			
Reference	**Parity**	**Balance limits**	**Amount control**	**Initialization**	**Redistribution**	**Price control**	**Price limits**	Resource provision	**Resource allocation**	**Counter-party**	**Peer selection**	**Decision making**	**Payment amount**	**Payment receiver**	**Karma Gain**	**Karma Loose**
P2P and Cloud Networks																
Telecommunication Networks																
Garcia and Hoepman (2004); Vishnumurthy (2008); Vishnumurthy et al. (2003)	P	N	S	I	N	A	R	P	P	P	M	F	B	P	P	C
Oliveira et al. (2011)	P	N	N	I	N	A	R	P	P	N	M	F	O	P	P	C
Mitra and Maheswaran (2005)	T	N	S,E	N	N	S	R	P	S	N	N	F	N	P	P	U,E
Telecommunication Networks																
Shen et al. (2014)	B	N	N	I	N	N	B	N	P	P	R	F	F	P	P	C
Efstathiou (2006)	T	N	N	N	N	N	N	P	P	N	R	F	F	P	P	C
Buttyán and Hubaux (2001, 2003); Mastronarde et al. (2015); Xu and van der Schaar (2013)	B	N	C	I	N	N	B	P	P	N	R	F	F	P	P	C
Road Transportation Networks																
Pedroso et al. (2023); van de Sanden (2022)	P	N	S	I	N	S	N	N	A	S	/	F	F	S	C	C
Censi et al. (2019); Elokda et al. (2023)	P	Y	C	I	N	A	R	N	S	P	R	F	B	P	P	C
Elokda et al. (2023, 2022)	P	N	C	I	N	A	N	N	S	S	M	F	B	A	P	C
Social Networks																
Prendergast (2022)	P	N	C	I	N	A	N	P	S	N	M	F	B	W	P	C
Johnson et al. (2014)	B	N	C	I	N	N	B	P	P	N	M	F	F	P	P	C
Kim et al. (2021); Roth et al. (2004); Sönmez et al. (2020)	B	N	N	N	N	N	B	P	P	P	M	F	F	P	P	C
Gale and Shapley (1962); Hylland and Zeckhauser (1979)	B	N	C	I	N	N	B	N	P	P	R	F	F	P	P	C

This table shows the different Karma design parameters for the applications. The following explains the abbreviations in this table of different options for the design parameters. The *parity*: P = price (resources can be traded for different amounts of Karma); B = binary (one resource can be traded for one unit of Karma); T = threshold (one needs a certain amount of Karma to be eligible to consume resources). The *balance limits*: N = no (agents can have as many or as few Karma points as they want); Y = yes (agents can have an amount of Karma which is limited by a lower bound and a defined upper bound). The *amount of control*: S = control by the system over time; N = no control; E = expiration of Karma units; C = constant number of Karma units. The *initialization*: I = equal initial endowment; N = no initial endowment. The *redistribution*: N = none. The *price control*: A = a market-like price determination, auctions; S = system-controlled prices; N = no price determination (in case of binary parity). The *price limits*: R = rational (prices above zero); B = binary (only one unit of Karma); N = none (all prices, including negative prices). The *resource provision*: P = an agent; N = the network/system. The *resource allocation*: S = system decides; P = up to the provider; A = always guaranteed to anyone who wins the auction/pays the price. The *counterparty*: P = pairs (with one other agent); N = multiple or all other agents (e.g., market, auction); S = the central system coordinator (e.g., system-defined prices). The *peer selection*: M = market; N = a local neighborhood/or a submarket suggested, respectively, guided by the system; R = random encounters that cannot be controlled by consumer and provider. The *decision-making*: F = agents are free to make their decisions (neglecting their urgency and needs). The *payment amount*: B = bid (used in auctions); O = order (system will calculate the costs); N = nothing; F = fix (fixed price or binary parity). The *payment receiver*: P = resource provider (resource provider receives); S = system (system receives); A = equal redistribution (to all participants); W = weighted redistribution (to all participants). The *Karma gain*: P = provision (earn Karma by providing resources); C = consumption (earn Karma by consuming in case of negative prices). The *Karma loose*: C = consumption (loose Karma by consuming resources); E = expiration of Karma points; U = untrustworthy behavior (system rule violation).

Table A5. Design parameter and options in different applications.

Design Parameter	Option		Exemplary References
			Currency
Parity	P	Price	Censi et al. (2019), Elokda et al. (2022), Elokda et al. (2023), Garcia and Hoepman (2004), Oliveira et al. (2011), Pedroso et al. (2023), van de Sanden (2022), Vishnumurthy et al. (2003), Vishnumurthy (2008),
	T	Threshold	Efstathiou (2006), Mitra and Maheswaran (2005)
	B	Binary	Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Gale and Shapley (1962), Hylland and Zeckhauser (1979), Johnson et al. (2014), Kim et al. (2021), Mastronarde et al. (2015), Prendergast (2022), Roth et al. (2004), Shen et al. (2014), Sönmez et al. (2020), Xu and van der Schaar (2013),
Balance limits	N	Unlimited	Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Efstathiou (2006), Elokda et al. (2022), Elokda et al. (2023), Gale and Shapley (1962), Garcia and Hoepman (2004), Hylland and Zeckhauser (1979), Johnson et al. (2014), Kim et al. (2021), Mastronarde et al. (2015), Mitra and Maheswaran (2005), Oliveira et al. (2011), Pedroso et al. (2023), Prendergast (2022), Roth et al. (2004), Shen et al. (2014), Sönmez et al. (2020), van de Sanden (2022), Vishnumurthy et al. (2003), Vishnumurthy (2008), Xu and van der Schaar (2013),
	Y	Bounded (upper, lower)	Censi et al. (2019), Elokda et al. (2023), Elokda et al. (2023),
Amount control	C	Constant	Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Censi et al. (2019), Elokda et al. (2022), Elokda et al. (2023), Gale and Shapley (1962), Hylland and Zeckhauser (1979), Johnson et al. (2014), Mastronarde et al. (2015), Prendergast (2022), Xu and van der Schaar (2013)
	S	System	Garcia and Hoepman (2004), Mitra and Maheswaran (2005), Pedroso et al. (2023), van de Sanden (2022), Vishnumurthy et al. (2003), Vishnumurthy (2008),
	N	Uncontrolled	Efstathiou (2006), Kim et al. (2021), Oliveira et al. (2011), Roth et al. (2004), Shen et al. (2014), Sönmez et al. (2020),
	N	Expiry	Mitra and Maheswaran (2005)
Initialization	I	Equal endowment	Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Censi et al. (2019), Elokda et al. (2022), Elokda et al. (2023), Gale and Shapley (1962), Garcia and Hoepman (2004), Hylland and Zeckhauser (1979), Johnson et al. (2014), Mastronarde et al. (2015), Oliveira et al. (2011), Pedroso et al. (2023), Prendergast (2022), Shen et al. (2014), van de Sanden (2022), Vishnumurthy et al. (2003), Vishnumurthy (2008), Xu and van der Schaar (2013),
		Weighted endowment	Not implemented but discussed in Gale and Shapley (2012); Prendergast (2022)
		Random endowment	None
	N	None	Efstathiou (2006), Kim et al. (2021), Mitra and Maheswaran (2005), Roth et al. (2004), Sönmez et al. (2020),
Redistribution		Property Tax	Not implemented, but discussed in Elokda et al. (2022), Elokda et al. (2023)
		Payment Tax	Not implemented, but discussed in Elokda et al. (2022), Elokda et al. (2023)
		Lottery	Not implemented, but discussed in Elokda et al. (2022), Elokda et al. (2023)
	N	None	Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Censi et al. (2019), Efstathiou (2006), Elokda et al. (2022), Elokda et al. (2023), Gale and Shapley (1962), Garcia and Hoepman (2004), Hylland and Zeckhauser (1979), Gale and Shapley (1962), Johnson et al. (2014), Kim et al. (2021), Mastronarde et al. (2015), Mitra and Maheswaran (2005), Oliveira et al. (2011), Pedroso et al. (2023), Prendergast (2022), Roth et al. (2004), Shen et al. (2014), Sönmez et al. (2020), van de Sanden (2022), Vishnumurthy et al. (2003), Vishnumurthy (2008), Xu and van der Schaar (2013),
			Interaction
Price control	A	Auction	Censi et al. (2019), Elokda et al. (2022), Elokda et al. (2023), Garcia and Hoepman (2004), Oliveira et al. (2011), Prendergast (2022), Vishnumurthy et al. (2003), Vishnumurthy (2008), Xu and van der Schaar (2013)
	S	Centrally defined	Mitra and Maheswaran (2005), Pedroso et al. (2023), van de Sanden (2022)
	N	None	Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Efstathiou (2006), Gale and Shapley (1962), Hylland and Zeckhauser (1979), Johnson et al. (2014), Kim et al. (2021), Mastronarde et al. (2015), Roth et al. (2004), Shen et al. (2014), Sönmez et al. (2020)
Price limits	R	Only positive	Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Censi et al. (2019), Elokda et al. (2023), Garcia and Hoepman (2004), Mastronarde et al. (2015), Mitra and Maheswaran (2005), Oliveira et al. (2011), Vishnumurthy et al. (2003), Vishnumurthy (2008), Xu and van der Schaar (2013)
	B	Binary	Gale and Shapley (1962), Hylland and Zeckhauser (1979), Johnson et al. (2014), Kim et al. (2021), Roth et al. (2004), Sönmez et al. (2020), Shen et al. (2014)
	N	None	Elokda et al. (2022), Elokda et al. (2023), van de Sanden (2022), Efstathiou (2006), Prendergast (2022), Pedroso et al. (2023)

Table A5. *Cont.*

Design Parameter	Option		Exemplary References
			Interaction
Resource provision	P	By agent	Censi et al. (2019), Elokda et al. (2022), Elokda et al. (2023), Pedroso et al. (2023), Shen et al. (2014), van de Sanden (2022)
	N	By system	Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Efstathiou (2006), Gale and Shapley (1962), Garcia and Hoepman (2004), Hylland and Zeckhauser (1979), Johnson et al. (2014), Kim et al. (2021), Mastronarde et al. (2015), Mitra and Maheswaran (2005), Oliveira et al. (2011), Prendergast (2022), Roth et al. (2004), Sönmez et al. (2020), Vishnumurthy et al. (2003), Vishnumurthy (2008), Xu and van der Schaar (2013)
Resource allocation	A	Auction winner	Pedroso et al. (2023), van de Sanden (2022)
	S	System decision	Censi et al. (2019), Elokda et al. (2022), Elokda et al. (2023), Mitra and Maheswaran (2005), Prendergast (2022)
	P	Provider decision	Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Efstathiou (2006), Gale and Shapley (1962), Garcia and Hoepman (2004), Hylland and Zeckhauser (1979), Johnson et al. (2014), Kim et al. (2021), Mastronarde et al. (2015), Oliveira et al. (2011), Roth et al. (2004), Shen et al. (2014), Sönmez et al. (2020), Vishnumurthy et al. (2003), Vishnumurthy (2008), Xu and van der Schaar (2013)
Counter-party	N	N agents	Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Efstathiou (2006), Johnson et al. (2014), Mastronarde et al. (2015), Mitra and Maheswaran (2005), Oliveira et al. (2011), Prendergast (2022), Xu and van der Schaar (2013)
	P	One agent (pairs)	Censi et al. (2019), Elokda et al. (2023), Gale and Shapley (1962), Garcia and Hoepman (2004), Hylland and Zeckhauser (1979), Kim et al. (2021), Roth et al. (2004), Shen et al. (2014), Sönmez et al. (2020), Vishnumurthy et al. (2003), Vishnumurthy (2008)
	S	System	Elokda et al. (2022), Elokda et al. (2023), Pedroso et al. (2023), van de Sanden (2022)
Peer selection	M	Market	Elokda et al. (2022), Elokda et al. (2023), Garcia and Hoepman (2004), Johnson et al. (2014), Kim et al. (2021), Oliveira et al. (2011), Prendergast (2022), Roth et al. (2004), Sönmez et al. (2020), Vishnumurthy et al. (2003), Vishnumurthy (2008)
	N	Neighbourhood	Mitra and Maheswaran (2005)
	R	Randomly assigned	Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Censi et al. (2019), Efstathiou (2006), Elokda et al. (2023), Elokda et al. (2023), Gale and Shapley (1962), Hylland and Zeckhauser (1979), Mastronarde et al. (2015), Shen et al. (2014), Xu and van der Schaar (2013),
		Active selection	Not implemented but discussed in Vishnumurthy et al. (2003), Vishnumurthy (2008)
Decision-making	F	Free	Elokda et al. (2022), Elokda et al. (2023), Shen et al. (2014), Oliveira et al. (2011), van de Sanden (2022), Efstathiou (2006), Mastronarde et al. (2015), Garcia and Hoepman (2004), Mitra and Maheswaran (2005), Johnson et al. (2014), Xu and van der Schaar (2013), Censi et al. (2019), Elokda et al. (2023), Hylland and Zeckhauser (1979), Gale and Shapley (1962), Prendergast (2022), Roth et al. (2004), Sönmez et al. (2020), Kim et al. (2021), Pedroso et al. (2023), Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Vishnumurthy et al. (2003), Vishnumurthy (2008),
Urgency process		Homogeneous	Censi et al. (2019), Elokda et al. (2022), Elokda et al. (2023), Elokda et al. (2023)
		Heterogeneous	Censi et al. (2019), Elokda et al. (2022), Elokda et al. (2023), Elokda et al. (2023)
Temporal preference		Homogeneous	Censi et al. (2019), Elokda et al. (2022), Elokda et al. (2023), Elokda et al. (2023)
		Heterogeneous	Censi et al. (2019), Elokda et al. (2022), Elokda et al. (2023), Elokda et al. (2023)
			Transaction
Payment amount	B	Bid, Peer's bid, Difference	Censi et al. (2019), Elokda et al. (2023), Elokda et al. (2023), Elokda et al. (2021), Garcia and Hoepman (2004), Prendergast (2022), Vishnumurthy et al. (2003), Vishnumurthy (2008)
	O	Order	Oliveira et al. (2011)
	F	Fixed	Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Efstathiou (2006), Mastronarde et al. (2015), Gale and Shapley (1962), Hylland and Zeckhauser (1979), Johnson et al. (2014), Kim et al. (2021), Pedroso et al. (2023), Roth et al. (2004), Shen et al. (2014), Sönmez et al. (2020), van de Sanden (2022), Xu and van der Schaar (2013)
	N	Nothing	Mitra and Maheswaran (2005)
Payment receiver	P	Resource provider	Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Censi et al. (2019), Efstathiou (2006), Gale and Shapley (1962), Garcia and Hoepman (2004), Hylland and Zeckhauser (1979), Johnson et al. (2014), Kim et al. (2021), Mastronarde et al. (2015), Mitra and Maheswaran (2005), Oliveira et al. (2011), Roth et al. (2004), Shen et al. (2014), Sönmez et al. (2020), Vishnumurthy et al. (2003), Vishnumurthy (2008), Xu and van der Schaar (2013)
	S	System	Pedroso et al. (2023), van de Sanden (2022)
	A	Equally across population	Elokda et al. (2022), Elokda et al. (2023), Elokda et al. (2023),
	W	Weighted average	Prendergast (2022)

Table A5. *Cont.*

Design Parameter	Option		Exemplary References
			Transaction
Karma gain	P	Resource provision	Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Censi et al. (2019), Efstathiou (2006), Elokda et al. (2022), Elokda et al. (2023), Elokda et al. (2023), Gale and Shapley (1962), Garcia and Hoepman (2004), Hylland and Zeckhauser (1979), Johnson et al. (2014), Kim et al. (2021), Mastronarde et al. (2015), Oliveira et al. (2011), Pedroso et al. (2023), Prendergast (2022), Roth et al. (2004), Shen et al. (2014), Sönmez et al. (2020), Vishnumurthy (2008), Vishnumurthy et al. (2003), Xu and van der Schaar (2013)
	C	Resource consumption	van de Sanden (2022), Pedroso et al. (2023)
Karma loose	C	Resource consumption	Buttyán and Hubaux (2001), Buttyán and Hubaux (2003), Censi et al. (2019), Efstathiou (2006), Elokda et al. (2022), Elokda et al. (2023), Elokda et al. (2023), Gale and Shapley (1962), Garcia and Hoepman (2004), Hylland and Zeckhauser (1979), Johnson et al. (2014), Kim et al. (2021), Mastronarde et al. (2015), Oliveira et al. (2011), Pedroso et al. (2023), Prendergast (2022), Roth et al. (2004), Shen et al. (2014), Sönmez et al. (2020), van de Sanden (2022), Vishnumurthy (2008), Vishnumurthy et al. (2003), Xu and van der Schaar (2013)
	E	Expiration	Elokda et al. (2022), Elokda et al. (2023), Mitra and Maheswaran (2005), Elokda et al. (2023),
	U	Rule-violation	Elokda et al. (2022), Elokda et al. (2023), Elokda et al. (2023), Mitra and Maheswaran (2005)

Table A6. Karma in different contexts.

Literature Field	Application Field
Blockchain	
	Reputation/credibility system
	Trust system
	Secure accounting system
	Micropayment system
	Trading system
	Information dissemination technology
	Scrip system
	Token economy
	Credit scheme
	Crypto currency
	Lightweight currency
	Technological prerequisite for...
	smart contracts
	distributed hash tables
	distributed ledger
	minting proof-of-work
Network and Technology	
	Network Protocol
	Self-Coordination in peer-to-peer computer networks
	Solution malicious behavior in peer-to-peer networks...
	free-riding problem
	hidden actions problem
	lotus eater attack
	Sybil attack
	Eclipse attack
	spoofing attack
Filesharing	
	Computation Resource Sharing
	File Sharing
Economics	
	Self-contained economy
	Non-monetary market
Game Theory	
	Dynamic population game
behavior	
	Incentive mechanism
	Fairness enforcement
	Altruism enforcement
	Contribution enforcement

Appendix B. Karma and Alternatives

See attached online Supplementary file.

Notes

1 The database queries were conducted on 1 October 2023.

2 Python package tomotopy (v.0.9.0, https://bab2min.github.io/tomotopy/v0.9.0/en/). Accessed on 1 October 2023.

3 https://medium.com/blockwhat/03-it-s-karma-484fdc2d8657. Accessed on 1 October 2023.

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