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Article / Book Information

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Title(English)	The evolution of cooperation in the unidirectional division of labour on networks with sanction systems
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種別(和文)	論文要旨
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（博士課程）
Doctoral Program

論 文 要 旨
THESIS SUMMARY

系・コース： Department of, Graduate major in	Innovation Science 系コース	申請学位（専攻分野）： Academic Degree Requested	博士 Doctor of (Engineering)
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要旨（英文 800 語程度）
Thesis Summary (approx.800 English Words)

The doctoral thesis entitled "The evolution of cooperation in the unidirectional division of labour on networks with sanction systems" critically investigates the effects of sanction systems on the evolution of cooperation (EOC) in the division of labour (DOL) on unidirectional linear and tree graph networks of groups. This scholarly study considers the DOL as asymmetric interactions among players and investigates the dynamics of the EOC using the evolutionary game theory.

This dissertation has been systematically divided into four comprehensive chapters, each intended to guide the reader toward a deep understanding of the subject matter.

Chapter 1 introduces the background and coordination of this research by discussing the previous studies on the DOL and the EOC. DOL is performing a large task by dividing it into smaller subtasks and allocating it to different people or companies, hence naturally creating complex networks of people. Often for a subtask, there can be multiple candidates based on the specialization, creating a group of individuals or companies for the same subtask present in the nodes of the DOL network. For having a successful DOL, cooperation is essential. However, the DOL on complex networks of groups has not been previously investigated from the perspective of the EOC in human society using evolutionary game theory. In the DOL, one player in a group interacts with another in the neighboring group and players in different groups often have an asymmetric relationship, which is considered here. Most of the previous studies of the EOC assumed that individuals are located on nodes of the network, neighbors interact together, and players have symmetric relationships. Therefore, this thesis challenges the new perspective from the viewpoint of the evolutionary game theory.

Chapter 2 discusses the studies of the DOL on the finite linear network. A cooperator in an upstream group produces and modifies a product, paying a cost of cooperation, and hands it to a player in a downstream group who obtains the benefit from the product, and if players in all roles cooperate, a final product can be completed. However, if a player in a group chooses defection, the DOL stops, the final product cannot be completed, and all players in all roles suffer damage. Two types of sanction systems are introduced, firstly the defector sanction system, where the exact defector is caught and sanctioned, and secondly, the first role sanction system, where if any defection happens, always the player in the first group is sanctioned. By using the replicator equations of the asymmetric game, and doing the local stability analysis of equilibria, which sanction system promotes the EOC compared to the sanction-less baseline system is investigated. It is found that the benefit of the product does not but the cost of cooperation matters to the evolutionary dynamics, and only the

defector sanction system promotes the coexistence of the cooperator and defector groups. The probability of finding a defector and the initial dominance of the cooperators determines which sanction system promotes the EOC in the linear DOL.

Chapter 3 discusses the study of the DOL on the finite tree graph network. From the network's original node called the premier group, a task flows and is divided along the branches. The settings are similar to the linear DOL, except that the tasks and damages through defection are divided along the branches. The two sanction systems mentioned in chapter 2 are again applied. A novel method to analyse the local stability of the equilibria of the replicator equations in the general tree network is developed. It is found that the EOC does not depend on the benefit from other's cooperation and the defections in the groups that are not directly related to that group's task. The defector sanction system promotes the coexistence of cooperator and defector groups and the EOC in the tree network. It is proved that a vertical increase in the network size hinders the EOC, however, the effects of horizontal increase are uncertain.

Chapter 4 concludes the thesis. The findings of previous chapters are summarized and the applications of this study are discussed. Particularly, the models are applicable in supply chains, subcontract systems, and bureaucratic systems. Finally, the future direction of this study is discussed. As the DOL has many other forms of network, the sanction systems are often hampered by corruption, and utilities are not always objective, there are various other possible expansions of this study.

In conclusion, this doctoral thesis expands the theoretical understanding of the EOC in the DOL. The generalization method of the mathematical models of DOL which is developed through this study shall ease further expansion of this study into more complex networks. It presents more scope of application of the theory of EOC in the socio-economic systems and thus contributes to system engineering. The proposed methodologies and the results obtained are believed to contribute to the advancement of innovation science, as the author argued. Based on the aforementioned, the present research merits the award of a Doctor of Engineering.