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System Dynamics Simulation to Reduce the Number of Patients with Lifestyle-Related Diseases and Medical Costs in Japan by Promoting Behavioral Change

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Abstract. Globally, many countries are about to become super-aging societies. This will likely be accompanied by a decrease in the ratio of working-age population and an increase in medical costs. In such societies, lifestyle-related diseases (LDs) account for a significant proportion of medical costs. LDs will gradually lead to disorders like hypertension, diabetes, and dyslipidemia, which may worsen and develop into more serious diseases. Therefore, it is important to promote behavioral change among the public to prevent the onset of LDs from the pre-disease stage. In this study, we developed a system dynamics model to simulate the number of patients with LDs and the medical costs, using statistical data in Japan as a case study. Utilizing two aging chains for each sex, which can describe the changes in the age-dependent structure of stocks, we represent populations of LD patients and non-LD patients by generation, and estimate changes in their population structure and associated medical costs by 2050. Compared with the current pace of change, by reducing the morbidity rate of LDs in each generation in line with their behavioral changes, we identify the effect of reducing the number of LD patients and medical costs. Furthermore, to effectively reduce these numbers, it is important to realize not just behavior change for a single generation but a series of behavior changes across generations. Thus, if statistical data are present, our model can predict the number of LD patients and medical costs for any country.

Keywords. System Dynamics, Lifestyle-related Diseases, Behavioral Change

Introduction

With the drop in mortality rates resulting from years of medical advances and improved diets, life expectancy has significantly increased worldwide. In 2019, the global average life expectancy was 70.8 years for men and 75.9 years for women due to the widespread availability of advanced medical care [1]. However, this growth has led to an increase in the proportion of older adults, resulting in many nations entering super-aging societies. This phenomenon is evident in developed and developing countries and poses serious challenges.

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As the population ages, its age structure undergoes changes that can lead to declining productivity and tax revenues of a country due to a diminishing proportion of working-age individuals. Additionally, an increase in the elderly population tends to raise medical costs, which can result in serious economic problems in the future. In such societies, lifestyle-related diseases (LDs) account for a significant proportion of the medical costs LDs, such as hypertension, diabetes, and dyslipidemia, can gradually worsen and develop into more serious diseases.

While the symptomatic appearance and progress of LDs are affected by various living practices, including diet, exercise, rest, smoking, and drinking [2][3], there is no established definition for each specific disease in this category. The Japanese Ministry of Health, Labour, and Welfare cites examples such as malignant neoplasms, diabetes, hypertension, heart disease, and cerebrovascular disease [4]. However, the term used globally to refer to LDs is "noncommunicable diseases," including chronic obstructive pulmonary disease [5]. Therefore, this study defines LDs as both LDs and noncommunicable diseases, taken as a whole.

Since LDs take a long time to develop, individuals must review their lifestyle habits, that is, make behavioral changes [6] in areas such as exercise, diet, and moderation in drink. Prochaska et al. proposed a transtheoretical model that requires intervention methods designed along five stages: precontemplation, contemplation, preparation, action, and maintenance [6]. Promoting these behavioral changes among the public is crucial to prevent the onset of LDs in the pre-disease stage. To support this endeavor, applications that monitor and provide advice on health conditions using mobile devices are being developed and tested [7][8][9].

To enable nationwide implantation of behavioral changes, a social system design that enables policymakers and governments to make informed decisions regarding the impact of LDs on the population structure is necessary. While previous studies have attempted to project future healthcare costs at the national and municipal levels, a design explicitly focusing on LDs has yet to be developed. Fukawa used microsimulation to analyze long-term care expenditure in Japan for older people without distinguishing between the sexes [10]. Chen et al. developed a model that projects the health conditions, disabilities, and functional status of Japan's elderly population [11], but, neither study focused on LDs. Nishi et al. used system dynamics (SD) to predict changes in healthcare costs following death prevention and the need for long-term care for the elderly in Japan [12]. However, their model only considered individuals aged 65 years and older, did not address all generations, and did not focus on specific diseases. The model only distinguished between elderly individuals who needed long-term care and those who did not. Ansah et al. examined the dynamic impact of different long-term care policies in Singapore using SD [13]. However, like in previous studies, their simulations did not focus on LDs and their nationwide impact on the population structure and medical costs.

Given the abovementioned situation, our study aims to answer the following research questions: 1) Which generation should be targeted for LD prevention, and to what extent? and 2) What reduction in LD patients and medical costs can be achieved through societal behavioral changes? To answer these questions, we developed an SD model that simulates the number of patients with LDs and associative healthcare costs. This is a transdisciplinary engineering approach [14] that crosses the border between system engineering and public health, thus supporting government policymaking. In Section 2, utilizing two aging chains for each sex, which can describe the changes in the age-dependent structure of stocks, we represent the populations of LD patients and non-LD patients by generation. Section 3 estimates the changes in population structure and associated medical costs by 2050 and identifies the impact of reducing the morbidity rate of LDs in each generation through behavioral changes. We also discuss additional measures that can effectively reduce the number of LD patients and medical costs. Section 4 addresses the remaining issues, and Section 5 concludes the paper.

1. Research Method: System Dynamics (SD) model

1.1. Developed SD model

This section describes the SD model developed for this study. Using population statistics from the Japanese Ministry of Internal Affairs and Communications and medical cost statistics from the Ministry of Health, Labour, and Welfare, we constructed two aging chains for LD patients and non-LD patients for each sex. The model focused on type 2 diabetes, obesity, dyslipidemia, cardiovascular diseases, COPD, hepatic diseases, and chronic kidney diseases as LDs. We excluded malignant neoplasms (cancers), since genetic factors play a significant role in their development and they are not always preventable through behavioral changes. Notably, our proposed model is highly versatile since statistical data are available for all diseases, and it is possible to select specific diseases for similar analysis based on the analyst's individual perspective.

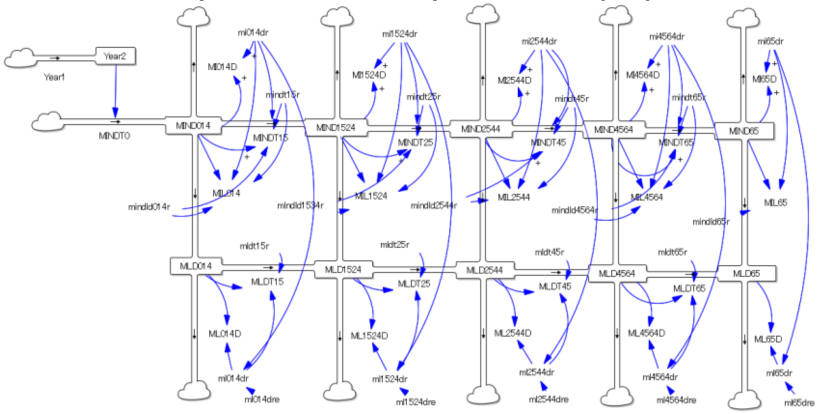


Figure 1. Proposed SD model for men.

Figure 1 depicts the SD model developed for men, where LD patients and non-LD patients are categorized into five age groups (0–14 years, 15–24 years, 25–44 years, 45–64 years, and 65+ years). For instance, the "MIND014" stock represents male non-LD patients between 0 and 14, while "MLD014" represents male LD patients of the same age group. Each stock has an outflow caused by death (e.g., MI014D and ML014D). The population of each stock moves between the stocks through flows (e.g., MINDT15 and MLDT15) due to aging. Additionally, flows were implemented where non-LD patients develop LDs (e.g., MIL014). Regarding the population transfer between stocks, the period from the age of inflow to that of outflow is considered a delay in each stock.

The sources used as initial data and the rate parameters that determined the flows are as follows. Compared to the previous model that dealt only with older adults [12], our model used a calculation period from 1920 to 2050, which covers all generations, to estimate demographics and medical costs for the whole country. The number of births from 1920 to 2020 was used as the source [15], while the number of births after 2021 was assumed to remain constant at the 2020 level. As there was insufficient simulated data for older generation stocks in the early part of the simulation period, this study discusses simulation results for data after 2010, when the first generation reached 90 years old. Mortality rates (e.g., mi014dr and ml014dr) were assigned to each generation stock. These parameters were set assuming that mortality declines from infancy to adolescence and then increases with age, in accordance with actual mortality trends, and that mortality is higher among those with LDs than those without. The morbidity rate of LDs (e.g., mindld014r) was calculated by dividing the number of LD patients by the population in each generation.

We used this stock-flow diagram to estimate the population structure and the structure of medical costs in the country by multiplying the population of each generation by the per capita medical cost. Per capita medical costs were obtained by summing the LD-related and non-LD-related medical costs for each generation and dividing by the number of patients in each generation.

1.2. Reference data

Following the Japanese government statistical data, we used the number of male and female births from 1920 to 2050 as the source data [15]. The number of LD patients and medical costs were compiled based on statistical data in 2020 for men and women [15]. The results are presented in Tables 1 and 2.

Table 1. Number of LD patients in 2020.

Age group (years)	Number of patients (men, thousands)	Morbidity rate (men, dimensionless)	Number of patients (women, thousands)	Morbidity rate (women, dimensionless)
0–14	2.8	0.00036359	2.2	0.00030010
15–24	2.8	0.00045440	2.2	0.00037511
25–44	24.9	0.0016807	16.1	0.0011292
45–64	172.9	0.010151	127.1	0.0074950
65+	520.3	0.033267	651.2	0.031942
Total	724.9	0.011811	800.6	0.012356

Table 2. Medical expenditure per capita for LD patients in 2020.

Age group (years)	Expenditure per capita (men, Yen)	Expenditure per capita (women, Yen)
0–14	7392900	8227300
15–24	7104700	6426200
25–44	7104700	6426200
45–64	7072900	4569600
65+	7015600	5090100
Total	7025100	5035200

We first examined the population structure while adjusting the mortality rates to ensure that the proposed SD model accurately reflects realistic demographics. The mortality rates were adjusted such that the population in 2020 was consistent with the statistical data. We used the per capita medical costs from 2020 as our reference values to calculate medical costs. Notably, this was the first trial of the model, and we used these rate parameters as constants throughout the simulation period. We will discuss the potential influence of long-term changes in these parameters later. The results of our calculations are presented in Section 2.

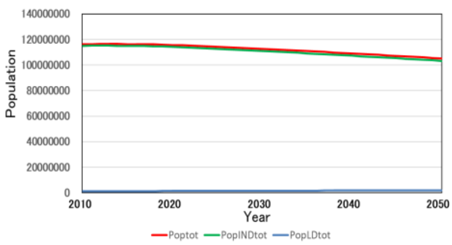
1.3. Validation of the SD model

We evaluated the validity of our model through three methods. Firstly, we calculated the mean absolute percentage error (MAPE) [16] between the statistical and calculated values for each generation's stock from 2010 to 2020. Since the government statistics on the number of patients were compiled every three years, MAPE was computed for 2011, 2014, 2017, and 2020. For men, MAPE ranged from 0.3 to 222.6 (mean 39.8), and for women, it ranged from 0.3 to 147.5 (mean 32.0). MAPE was higher in the 0–14 and 15–24 age groups, with the highest value observed in the 15–24 age stock for both sexes. Notably, the statistics on the number of LD patients were rounded to the nearest 100. The number of LD patients in this generation was only 2,200 for men and 2,800 for women, which could have reduced the statistical accuracy of each LD case. The MAPE for the other generations ranged from 0.3 to 22.0 (mean 11.9) for men and from 0.3 to 34.3 (mean 15.3) for women. Secondly, we checked the model parameters concerning the mortality rates and per capita medical costs. Thirdly, we compared the morbidity of LDs between men and women and confirmed no extreme differences.

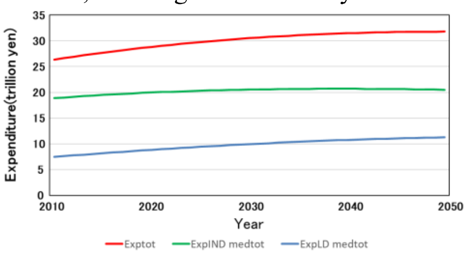
2. Simulation Results

2.1. Reduction in the morbidity rate of LDs in each generation

Figures 2(a) and 2(b) present the estimated values of the total population and medical costs from 2010 to 2050. In Figure 2(a), the blue line represents the number of LD patients, the green line represents the number of non-LD patients, and the red line represents their total. In Figure 2(b), the blue line represents the medical costs for LD patients, the green line represents the medical costs for non-LD patients, and the red line represents their total. In 2020, the population was 115,670.2 thousand people, with 56,332.1 thousand men and 59,338.1 thousand women. The number of LD patients was 1,477.0 thousand, with 692.7 thousand men and 784.3 thousand women, which agreed with the Japanese population statistics with an accuracy of 93.7% to 96.8%. The total medical costs in 2020 were 28.82 trillion yen, with 14.19 trillion for men and 14.63 trillion for women. The medical costs for LD patients were 8,85 trillion yen, with 4.87 trillion for men and 3.98 trillion for women, which agreed with the medical cost statistics with 93.6% and 97.0% accuracy. The medical costs for LD patients gradually increased from 2010 to 11.27 trillion yen in 2050, while the medical costs for non-LD patients gradually declined after reaching a peak in 2039, to 20.49 trillion yen in 2050. The total medical costs were estimated to be the sum of these, reaching 31.76 trillion yen in 2050.



(a)



(b)

Figure 2. Total population (a) and total medical expenditure (b).

To reduce the number of LD patients and associated medical costs, we examined the following scenarios (S1–S3) for both men and women, as the effect of LD prevention through behavioral changes

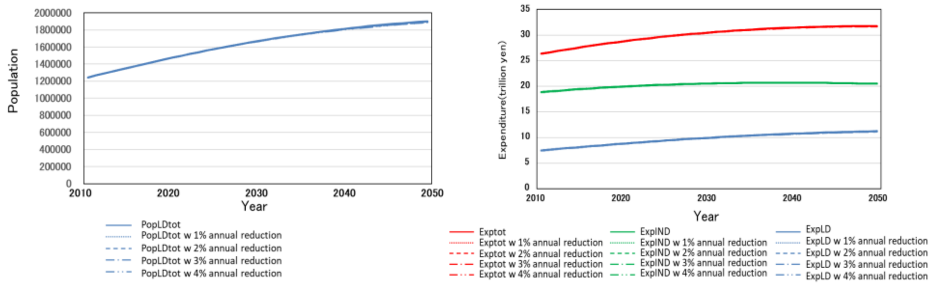
S1: To reduce the morbidity rate of LDs in the 25–44 age group from 2024.

S2: To reduce the morbidity rate of LDs in the 45–64 age group from 2024.

S3: To reduce the morbidity rate of LDs in the 65+ age group from 2024.

In implementing these scenarios, we prepared look-up variables showing a decrease in the morbidity rate of LDs from 2024 to 2050 owing to the effects of behavioral changes. Four different annual reduction rates were considered, ranging from 1% to 4%. The results of these simulations are shown in Figures 3 and 5. In each figure, the solid, chain, dashed, single dot, and double dot lines correspond to no reduction, 1%, 2%, 3%, and 4% annual reduction in the morbidity rate of LDs, respectively.

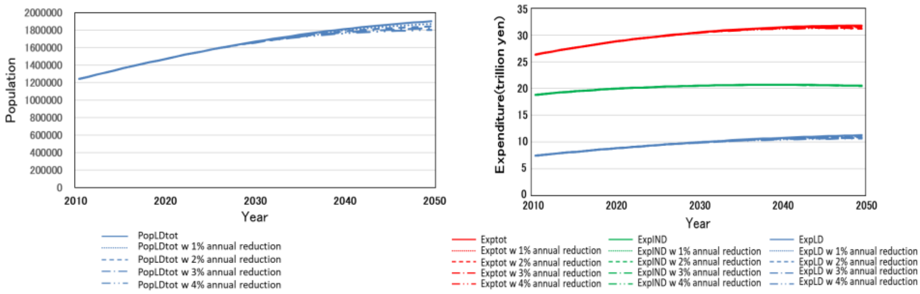
In Scenario S1, the total number of LD patients, including both men and women, decreased slightly from 1,903 thousand to 1,887 thousand in 2050 (from 828 thousand to 819 thousand people for men; from 1,075 thousand to 1,069 thousand for women), resulting in a total reduction in the number of patients of 0.81%. Regarding medical costs, the total medical costs in 2050 decreased slightly from 31.76 trillion to 31.66 trillion yen (from 14.92 trillion to 14.86 trillion yen for men and from 16.84 trillion to 16.80 trillion yen for women), and medical costs for LD patients decreased slightly from 11.27 trillion yen to 11.17 trillion yen (from 5.82 trillion yen to 5.75 trillion yen for men and from 5.45 trillion yen to 5.41 trillion yen for women). The total reduction in medical costs for LD patients was 0.90%, corresponding to approximately 100 billion yen. These results indicate that the effect of behavioral changes was small only in the 25–44 age group.



(a) (b)

Figure 3. Total population (a) and total medical expenditure (b) for S1.

In Scenario S2, the total number of LD patients, including men and women, decreased from 1,903 thousand to 1,803 thousand in 2050 (from 828 thousand to 769 thousand for men; from 1,075 thousand to 1,033 thousand for women). The total reduction in the number of LD patients was 5.26%. The total medical costs in 2050 decreased from 31.76 trillion to 31.18 trillion yen (from 14.92 trillion to 14.53 trillion yen for men and 16.84 trillion to 16.65 trillion yen for women). Specifically, the medical costs for LD patients decreased from 11.27 trillion to 10.66 trillion yen (from 5.82 trillion to 5.41 trillion yen for men and 5.45 trillion to 5.25 trillion yen for women). The total reduction in medical costs for LD patients was 5.40% (approximately 610 billion yen). As in S1, the effect of behavioral changes is limited only in the 45–64 age group.

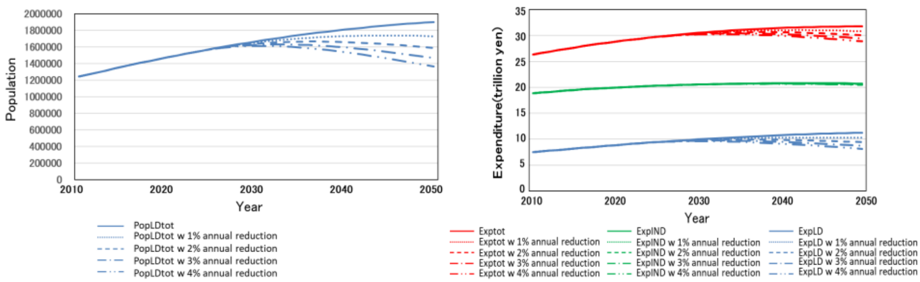


(a) (b)

Figure 4. Total population (a) and total medical expenditure (b) for S2.

In Scenario S3, the total number of LD patients (men and women) decreased from 1,903 thousand to 1,368 thousand by 2050 (from 828 thousand to 618 thousand for men; from 1,075 thousand to 751 thousand for women). This decrease represents a 28.09% reduction in overall number of LD patients, indicating that reducing the morbidity rate of LDs in this generation was the most effective strategy. The total medical costs in 2050 decreased from 31.76 trillion to 28.87 trillion yen (from 14.92 trillion to 13.54 trillion yen for men and 16.84 trillion to 15.33 trillion yen for women). Specifically, the medical costs for LD patients decreased from 11.27 trillion to 8.14 trillion yen (from 5.82 trillion to 4.35 trillion yen for men and 5.45 trillion to 3.80 trillion yen for women). The total reduction in medical costs for LD patients was 27.74% (approximately 3.13 trillion yen), resulting in a similarly significant cost reduction.

Although scenario S3 seems good, a 4% annual reduction in the morbidity rate of LDs is an optimistic scenario. By 2050, the morbidity rate will be only 33% of that in 2020. The feasibility of this scenario remains unclear. Therefore, we explore a more realistic scenario in the next section.



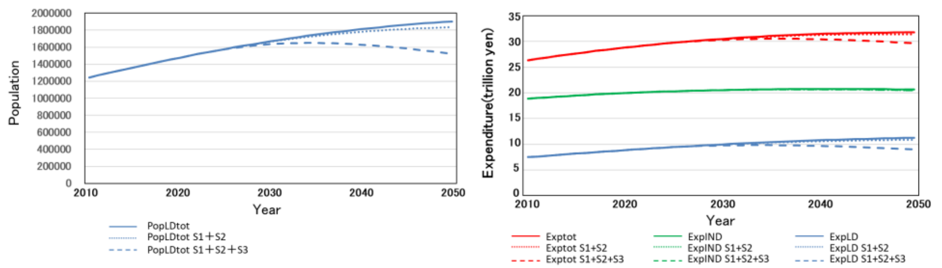
(a) (b)

Figure 5. Total population (a) and total medical expenditure (b) for S3.

2.2. Reduction in morbidity of LDs across generations

To explore a more realistic solution, we investigated scenarios promoting behavioral changes across multiple generations. We set the annual reduction in the morbidity rate of LDs to 2%, which is relatively moderate (the morbidity rate in 2050 corresponds to 58% of that in 2020). Further, we analyzed two additional patterns, S1+S2 and S1+S2+S3, as Scenario 4 (S4). The results are presented in Figure 6, where the solid, chain, and dashed lines show no reduction in the morbidity rate, S1 + S2, and S1 + S2 + S3, respectively.

In Scenario S4, the total number of LD patients in 2050 (men and women) decreased from 1,903 thousand to 1,835 thousand in the case of S1 + S2 and to 1,520 thousand in the case of S1 + S2 + S3 (for men, from 828 thousand people to 788 thousand in S1 + S2 and 664 thousand in S1 + S2 + S3; for women, from 1,075 thousand to 1,047 thousand in S1 + S2 and 856 thousand in S1 + S2 + S3). This decrease represents a 20.11% reduction in the number of LD patients. Total medical costs in 2050 decreased from 31.76 trillion to 31.36 trillion yen in the case of S1 + S2 and to 29.66 trillion yen in the case of S1 + S2 + S3 (for men, from 14.92 to 14.66 trillion yen in S1 + S2 and to 13.84 trillion yen in S1 + S2 + S3; for women, from 16.84 to 16.71 trillion yen in S1 + S2 and to 15.82 trillion yen in S1 + S2 + S3). Specifically, the medical costs for LD patients decreased from 11.27 trillion yen to 10.85 trillion yen in the case of S1 + S2 and to 9.01 trillion yen in the case of S1 + S2 + S3 (for men, from 5.82 to 5.54 trillion yen in S1 + S2 and to 4.67 trillion yen in S1 + S2 + S3; for women, from 5.45 to 5.31 trillion yen in S1 + S2 and to 4.34 trillion yen in S1 + S2 + S3). The total reduction in medical costs for LD patients was 20.05% (approximately 2.26 trillion yen). These results indicate that S1 + S2 + S3 is a realistic and effective strategy, highlighting the importance of behavioral changes across multiple generations to reduce the morbidity rates of LDs.



(a) (b)

Figure 6. Total population (a) and total medical expenditure (b) for S4.

3. Discussion

This section examines the long-term variations in key rate parameters and their impact on the simulation results. First, the Japanese government population statistics allowed us to calculate mortality rates every five years from 1950 to 2010 and every year afterward. We found that mortality rates used in the simulation were higher than the statistical values for the 0–14 and 65+ age groups, within the statistical range for the 14–24 and 25–44 age groups, and slightly lower than the statistical values for the 45–64 age group. These differences can be attributed to the higher mortality rate before 1950 for the 0–14 age group and the declining mortality rate for the 65+ age group due to medical advancements. Although these long-term variations exist, we found that the parameters used in the simulation are reasonable and not far apart.

Second, we discuss the long-term variations in morbidity rates of LDs. Statistics on the number of patients per disease case for both men and women were compiled only after 1999. We found that the number of LD patients may be less accurate, particularly for younger generations. The morbidity rate of LDs in the 45–64 and 65+ age groups gradually increased as it moved back in time. These facts may have affected the relatively high MAPEs in the simulation.

Finally, we discuss the long-term variations in per capita medical costs for LD patients. The medical costs per disease case since 2011 for both men and women were examined. We found that the costs for the 0–14 age group may also be less accurate due to the less accurate number of LD patients in the group, while those for the 45–64 and 65+ age groups increased gradually. Notably, while per capita medical costs can also change over time, they are just unit costs for estimating medical costs for each year and are not affected over the entire simulation period, as is the case with population structure.

Despite these issues, the achievement of this study is that we succeeded in developing a framework for long-term social structure design and providing an approximation of the overall picture. If necessary, the model can be further developed to account for long-term variations in the discussed parameters.

Before concluding this section, we discuss the realization of behavioral changes in reducing the morbidity rate of LDs and medical costs. This study simulated the effects of behavioral changes, but further research is needed to specify how to realize them in practice, promoting and managing the five stages of the transtheoretical model over the long term [6]. For instance, Mitchell et al. showed that a multicomponent intervention that offered a small immediate reward (loyalty points) for achieving a personalized daily step goal increased daily steps on a population scale, especially those who were physically inactive [17]. In their 12-week experiment, 32,229 participants (average age 33.7 years) walked 115.70 more steps compared to their own baseline [17]. Yoshizawa et al. reported that a 9-month lifestyle-based physical activity intervention program for 60 adults (average age 63.1 years) resulted in $US 640.4/year and $US 369.1/year reduction in total and outpatient expenditures, and a 6.47-fold higher odds ratio for outpatient visits [18]. These can be used as supporting evidence that behavioral changes can reduce the morbidity rate of LDs. In addition, we suggested disseminating proactive intervention services that utilize appropriate digital technologies to encourage behavioral and lifestyle changes, such as dietary and exercise habits [19]. Overall, this study provides valuable insights into the long-term social and economic impact of LDs and the potential benefits of preventive measures.

4. Conclusion

This paper proposed a System Dynamics (SD) model that simulates the number of patients with LDs and associated medical costs. Analyzing statistical data in Japan as a case study, we specified populations of LD patients and non-LD patients by generation and estimated changes in their population structure and medical costs up to 2050. Our results indicate that reducing the morbidity rate of LDs through behavioral changes can significantly reduce the number of LD patients and medical costs. Particularly, we found that these numbers were effectively reduced not only by behavioral change of a single generation, but also by a series of behavioral changes across multiple generations. Overall, we successfully obtained a 20.11% reduction in the number of LD patients and a 20.05% decrease in medical costs for LD patients through our proposed model.

It is worth noting that the versatility of the proposed SD model allows it to predict the number of LD patients and medical costs in any country if relevant statistical data are available. Additionally, this study represents a transdisciplinary engineering effort that bridges gaps between system engineering and public health. The results of our research can provide valuable insights for government policymaking. They may also encourage the development of new services involving medical care and information technology to promote behavioral changes.

References

[1] N.N., *Life expectancy and Healthy life expectancy Data by World bank income group*, World Health Organization, https://apps.who.int/gho/data/view.main.SDG2020LEXWBv?lang=en (cited 2023 Feb 18).

[2] N.N., *Annual Reports on Health and Welfare 1998-1999 Social Security and National Life: Section 4. Promoting Lifelong Health and Regional Health*, Ministry of Health, Labour and Welfare, https://www.mhlw.go.jp/english/wp/wp-hw/vol1/p2c6s4.html (cited 2023 Feb 18).

[3] L. B. Larsen, A. L. Sonderlund, J. Sondergaard, J. L. Thomsen, A. Halling, N. C. Hvidt, E. A. Hvidt, T. Mønsted, L. B. Pedersen, E. M. Roos, P. V. Pedersen, and T. Thilsing, Targeted prevention in primary care aimed at lifestyle-related diseases: a study protocol for a non-randomised pilot study, *BMC Family Practice*, 2018, 19:124, https://doi.org/10.1186/s12875-018-0820-8.

[4] Ministry of Health, Labour and Welfare, Seikatsusyukanbyo toha?, https://www.e-healthnet.mhlw.go.jp/information/metabolic/m-05-001.html (in Japanese, cited 2023 Feb 18)

[5] N.N., *Noncommunicable diseases*, World Health Organization, https://www.who.int/news-room/fact-sheets/detail/noncommunicable-diseases (cited 2023 Feb 18).

[6] J. O. Prochaska, and W. F. Velicer, The Transtheoretical Model of Health Behavior Change, *American Journal of Health Promotion*, 1997, Vol, 12, No. 1, pp. 38–48.

[7] C. S. Bloss, N. E. Wineinger, M. Peters, D. L. Boeldt, L. Ariniello, J. Y. Kim, J. Sheard, R. Komatireddy, P. Barrett, and E. J. Topol, A prospective randomized trial examining health care utilization in individuals using multiple smartphone-enabled biosensors. *PeerJ*, 2016, Vol. 4:4, e1554.

[8] S. C. Sepah, L. Jiang, R. J. Ellis, K. McDermott, A. L. Peters, Engagement and outcomes in a digital Diabetes Prevention Program: 3-year update, *BMJ Open Diabetes Research and Care*, 2017, Vol. 5, e000422.

[9] M. Kanai, T. Toda, K. Yamamoto, M. Akimoto, and Y. Hagiwara, A Mobile Health-Based Disease Management Program Improves Blood Pressure in People with Multiple Lifestyle-Related Diseases at Risk of Developing Vascular Disease –A Retrospective Observational Study–, *Circulation Reports*, 2022, Vol. 4, pp. 322–329.

[10] T. Fukawa, Health and long-term care expenditures of the elderly in Japan using a micro-simulation model. *The Japanese Journal of Social Security Policy*, 2007, Vol. 6, No. 2, pp. 199–206.

[11] B. K. Chen, H. Jalal, H. Hashimoto, S. Suen, K. Eggleston, M. Hurley, L. Schoemaker, and J. Bhattacharya, Forecasting Trends in Disability in a Super-Aging Society: Adapting the Future Elderly Model to Japan, *Journal of the Economics of Ageing*, 2016, Vol. 8, pp. 42–51.

[12] N. Nishi, N. Ikeda, T. Sugiyama, K. Kurotani, and M. Miyachi, Simulating the Impact of Long-Term Care Prevention Among Older Japanese People on Healthcare Costs From 2020 to 2040 Using System Dynamics Modeling, *Frontiers in Public Health*, 2020, Vol. 8, Article 592471.

[13] J. P. Ansah, R. L. Eberlein, S. R. Love, M. A. Bautista, J. P. Thompson, R. Malhotra, D. B. Matchar, Implications of long-term care capacity response policies for an aging population: A simulation analysis, *Health Policy*, 2014, Vol. 116, pp. 105–113.

[14] N. Wognum, C. Bil, F. Elgh, M. Peruzzini, J. Stjepandić, and W.J.C. Verhagen, Transdisciplinary engineering research challenges. *Advances in Transdisciplinary Engineering*, 2018, Vol. 7, pp. 753-762.

[15] Portal Site of Official Statistics of Japan, e-Stat, https://www.e-stat.go.jp/en/stat-search?page=1&bunya_l=15 (cited 2023 Jan 6)

[16] J. Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World*, McGraw-Hill, Boston, 2000.

[17] M. Mitchell, L. White, E. Lau, T. Leahey, M. A. Adams, and G. Faulkner, Evaluating the Carrot Rewards App, a Population-Level Incentive-Based Intervention Promoting Step Counts Across Two Canadian Provinces: Quasi-Experimental Study, *Journal of Medical Internet Research Mhealth Uhealth*, 2018, Vol. 6, Iss. 9, e178.

[18] Y. Yoshizawa, J. Kim, and S. Kuno, Effects of a Lifestyle-Based Physical Activity Intervention on Medical Expenditure in Japanese Adults: A Community-Based Retrospective Study, *BioMed Research International*, 2016, 7530105.

[19] M. Toriya, T. Kimura, S. Kawai, M. Fukuhara, T. Kimura, Y. Washitani, M. Ide, M. Takaramoto, K. Narazaki, H. Suzuki, and T. Toma, Proposal for an intervention service digital platform to promote health behaviors (in Japanese), *44th Research Conferences at Japan Creativity Society, Session B*, 2022.