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Modeling of Municipal Solid Waste Management System Using Powersim Studio–A Case Study

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Abstract—*The objective of the present study is system dynamics modeling of Municipal Solid Waste Management using software powersim. The elements of system dynamics modeling include population, collection, storage, transportation and disposal of solid waste along with growth state development product (GSDP), municipal budget and collection efficiency. Municipal solid waste (MSW) are all the wastes generated from residential, commercial and institutional areas such as street sweepings, stores, markets, restaurants and hotels, which are discarded as useless or unwanted. The improper management of MSW constitutes a growing concern for cities in developing nations. Generally, in India, MSW is disposed of in low-lying areas without taking any precaution and operational control. Therefore, municipal solid waste management (MSWM) is one of the major environmental problems of Indian megacities.*
Process analysis and selection is one of the most challenging aspects of the municipal solid waste management system (MSWMS) modeling. Both theoretical knowledge and practical experience are necessary in the MSWMS modeling. MSWMS modeling is done for maximum efficiency within a certain flow range and municipal solid waste characteristics. Hence accurate measurement of municipal solid waste generated, treated and disposed are required.

1. INTRODUCTION

Proper management of various components such as generation, collection, storage, transfer and transport, processing/treatment and final disposal is termed as Municipal Solid Waste Management (MSWM). It requires proper infrastructure, maintenance and up-gradation for all activities. The objective of MSWM is to reduce the MSW quantity disposed of on land by recovery of materials and energy from MSW in a cost effective and environment friendly manner. The interrelationship of these functional elements is shown in Fig. 1 [2, 11]. Data on quantity variation and generation rate are useful in planning of collection and disposal systems. MSW generation rates are affected by geographic location, frequency of collection, socioeconomic development, degree of industrialization, and the climate. Generally, the greater the economic prosperity and the higher percentage of urban population, the greater the amount of MSW produced [15].

With increasing urbanization and changing life styles, Indian cities now generate 8 times more MSW than they used to in 1947. Presently, about 90 million tons of solid waste is being generated annually as by-products during industrial, mining, municipal, agricultural and other processes. The amount of MSW generated per capita is estimated to increase at a rate of 1-1.33% annually [14]. Host of researchers [5, 9, 15] have reported that the MSW generation rates in small towns are lower than that of metro-cities, and the per capita generation rate of MSW in India ranges from 0.2 to 0.5 Kg/day. It is also estimated that total MSW generated by 217 million people living in urban areas is 23.86 million tons/year by 1991 and it crosses 39 million tons by 2001.

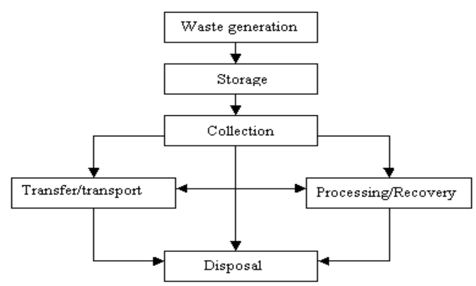

Fig. 1: Interrelationship among functional elements of SWM system

Powersim Studio

Simulations in Powersim Studio are based on system dynamics. System dynamics is a computer- based simulation modeling methodology developed at the Massachusetts Institute of Technology(MIT) in the 1950s as a tool for managers to analyze complex problems. Its primary audience is still managers, although it has spread widely in academia, where professors and students use it to model systems from every conceivable discipline ranging from history and literature to biology, physics, and economics. Using system dynamics simulations allows us to see not just events, but also patterns of behavior over time. The behavior of a system often arises out of the structure of the system itself, and behavior usually changes over time. Sometimes the simulation looks backward, to historical results. At other times it looks forward into the future, to predict possible future results. System dynamics simulations are good at communicating not just what might happen, but also why. This is because system dynamics simulations are designed to correspond to what is, or might be happening, in the real world.

System dynamics simulations are based on the principle of cause and effect, feedback, and delay. Some simple simulations will incorporate only one or two of these principles. More sophisticated simulations will use all three to produce the kind of behavior we encounter in the real world. The four main elements, which are the main elements of all SD software, are stocks or levels, flows or rates, converters and connectors as shown in Fig. 2.

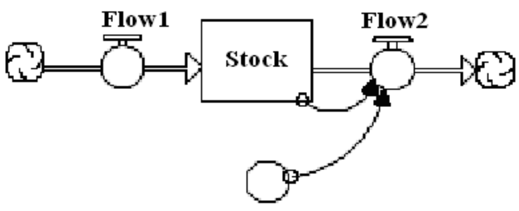

Fig. 2: Basic elements of system dynamics

The structure of SD is presented by causal loop diagrams (CLD), which capture the major feedback mechanisms (Fig. 3). A CLD is a diagram that aids in visualizing how interrelated variables affect one another. It plays two important roles in SD: they serve as preliminary sketches of causal hypotheses during model development; and they can simplify the representation of a model. The diagram includes elements and arrows (which are called causal links) linking these elements together in the same manner and a sign (either + or -) on each link. A causal link from one element A to another element B is positive (+) if either A adds to B or any increase or decrease in A causes a change in B in the same direction. A causal link from one element C to another element D is negative (-) if either C subtracts from D or any increase or decrease in C causes a change in D in the opposite direction.

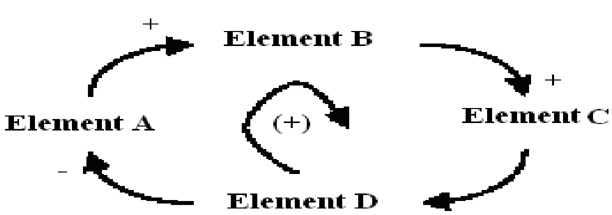

Fig. 3: Causal loop diagram

2. METHODOLOGY

Initial step of SD modeling approach is the identification of problem followed by development of dynamic hypothesis explaining the causes of the problem. The dynamic model is converted to the causal loop diagrams or stock flow diagrams, which are based on the inter linkage of different components associated within the system. This model formulation is normally designed to test a computer simulation model with regard to the alternative policies within the system. In SD modeling, simulations are time dependent. To develop SD models, the relevant study material can be found in the literature. As far as SWM is concerned, the prediction of waste generation plays an important role in the management system. Traditional forecasting methods frequently count on the demographic and socioeconomic factors on a per-capita basis. In order to forecast the MSW generation of a complex waste management system, a SD model has been proposed. In this study Powersim Studio Academic 2005 software was used to support the analysis and study of MSWM system in Delhi. The mathematical mapping of a SD stock-flow diagram occurs via a system of differential equations, which is solved numerically via simulation. Nowadays, high-level graphical simulation programs (such as Powersim) support the analysis and study of these systems. The real power of SD is utilized through simulation. Although it is possible to perform the modeling in a spreadsheet, there is a variety of software packages that have been optimized for this. The steps involved in a simulation are:

- Define the problem boundary.
- Identify the most important stocks and flows that change these stock levels.
- Identify sources of information that impact the flows.
- Identify the main feedback loops.
- Draw a causal loop diagram that links the stocks, flows and sources of information.
- Write the equations that determine the flows.
- Estimate the parameters and initial conditions. These can be estimated using statistical methods, expert opinion, market research data or other relevant sources of information.
- Simulate the model and analyze results.

3. SYSTEM DYNAMICS MODEL FOR MSWM

The causal loop diagram has presented in Fig. 4 depicts the relationships between the essential elements of MSWMS in Delhi and the influencing factors. An important issue is that the amount of MSW generation increases with the increase in population and growth economic (GSDP and per capita income). If the MSW generated is disposed of in an inappropriate way it will negatively affect the environment and cause environmental problems then the funds required for managing this waste will be increased causing deficit in the municipal budget. The environmental effects can be minimized by applying an integrated municipal solid waste management system (IMSWMS). The environmental problems have a strong influence on the three main factors: legal, economic and social patterns. Firstly, the legislative rules set up goals and standards to regulate the impact of the different treatment technologies. Thus, goals and standards contribute to the establishment of MSWMS through waste management plans (MSWMP). Secondly, the environment problems lead to economic burden for municipalities, governments and indirectly for the general public as well. In order to decrease further the environmental problems and to create revenues and fund for MSWM, a tax system is introduced. This also stimulates the IMSWMS by promoting the appropriate treatment methods, which can also help in covering the deficit in the municipal budget. In addition, increasing public awareness about different problems associated with MSW may help in source segregation and reduction, thus reinforcing the MSWMS.

System Dynamics Modeling for the Year 2001 – 2010

The baseline scenario is simulation of MSWMS in Okhla between 2001 and 2010. The baseline scenario can be considered as reference scenarios to which other scenarios can be compared. The initial population of Okhla for the year 2001 was 1,25,474. The decadal average population growth rate for 2001-2010 (Civic Guide, Municipal Corporation of Delhi), data on Gross State Domestic Product (GSDP) for Delhi was collected for the period 2001-2010 and the annual growth rate and the per capita GSDP were estimated for the same period. The per capita MSW generation rate was taken as 7.1 t/yr in 2001. The relationship between the per capita GSDP and the per capita MSW generation rate was estimated and then the per capita MSW generation rate was determined.

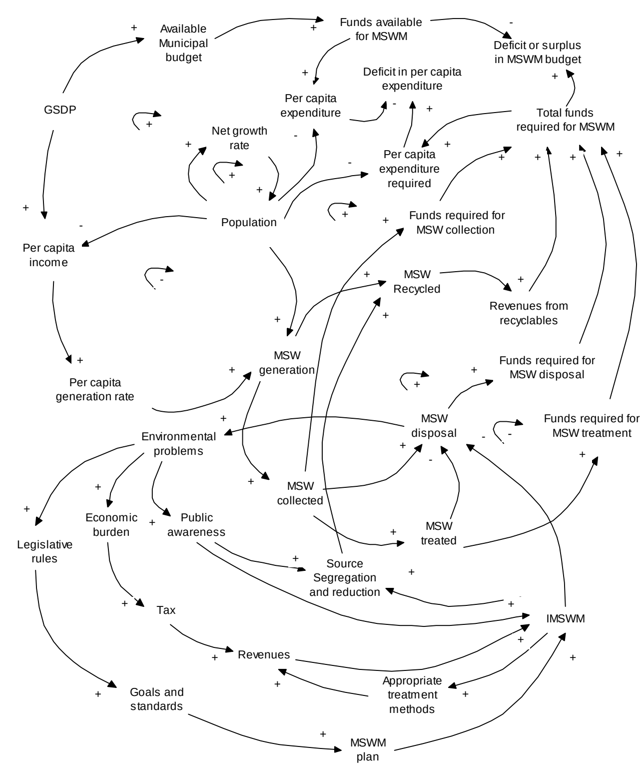

Fig. 4: Causal loop diagram of MSWMS

The population and per capita generation rate can give the amount of MSW generated for the city. The recyclables fraction of waste ranges from 13-20% (MCD, 2005, 2006; NDMC, 2005,2006). The initial value of recyclables fraction was taken as 20% for the year 2001. This fraction will grow at rate of 0.005 yearly. It is assumed that the recycling efficiency is 50%. The recycling system involves the formal sector, the municipal body and a large informal sector that consists of many actors such as rag pickers, itinerant buyers, small scrap dealers and wholesalers, which are responsible for recycling of MSW. The informal sector's involvement in recycling of MSW is making it highly efficient. Using the previous data the amount of recycled waste can be estimated, then the amount of collected MSW using 80% the collection efficiency and the amount of MSW left without collection can be estimated (TERI, 2003).

It is assumed that 25 % of waste treated through composting is converted to compost, 10% is left as residue, which contribute to the MSW going for landfills and the rest lost due to respiration and evaporation (MCD, 2004). The three existing landfills are receiving collected MSW and the remaining residues of the other processes like recycling and composting plants. The funds required for MSWM depend on the funds required for MSW storage, collection and transportation and the annual operating and maintenance costs for landfills and composting plants. It is assumed that MSW storage; collection and transportation consume 90% of the total funds available for MSWM (MCD, 2006). The funds available for MSWM depend on the economic growth (GSDP), which in turn influence municipal budget. The per capita expenditure for MSWM depends on population and the funds available for MSWM.

To develop a quantitative model the causal loop diagram is converted to stock flow diagram, which explains the physical as well as the information flows among various elements of the MSWM model. The detailed stock flow diagram of MSWM model is explained in Fig. 5. The MSWMS is depicting the interaction of MSW generation and population, per capita GSDP and per capita MSW generation rate. The system also defines the quantity of MSW collected, uncollected, recycled, composted and disposed of in landfills. In addition, the system determines the funds required for MSWM and the surplus or deficit in MSWM budget. The MSW generated is considered to be product of the two variables: the population (P) and the per capita MSW generation rate (MSW_{pc}). The per capita generation rate increase with the increases in per capita GSDP ($GSDP_{pc}$), which in turn influenced by the economic growth (GSDP), urbanization rate and the living standards of the residents in the city. The annual MSW generation is computed using the following dynamo equations:

$$MSW_g = P * MSW_{pc}$$

Where, $P = P_{initial} * (1 + \text{annual net growth rate})^{n}$; n= year

$MSW_{pc} = f(GSDP_{pc}, \text{time})$

The MSW collected (MSW_c) depends on the collection efficiency (C_{eff}) and the quantity of MSW recycled (MSW_r), which calculated from the recyclables fraction (R_{fr}) and recycling efficiency (R_{eff}) and affected by the annual growth rate of R_{fr}. The following equations can be used to determine MSW_c, MSW_r and MSW uncollected (MSW_{unc})

$$MSW_c = C_{eff} * (MSW_g - MSW_r)$$

$$MSW_r = R_{fr} * R_{eff} * MSW_g$$

$$MSWunc = MSW_g - (MSW_c + MSW_r)$$

The amount of MSW composted (MSW_{comp}) depends on the operation efficiency for the composting plants. The initial design capacity of composting plants is 342.46 t/day in 2001. It is assumed that 25 % of waste treated through composting is converted to compost. The amount of MSW, which disposed of at landfills (MSW_{dis}) depends on MSW_c and MSW_{comp}

$$MSW_{dis} = MSW_c - MSW_{comp}$$

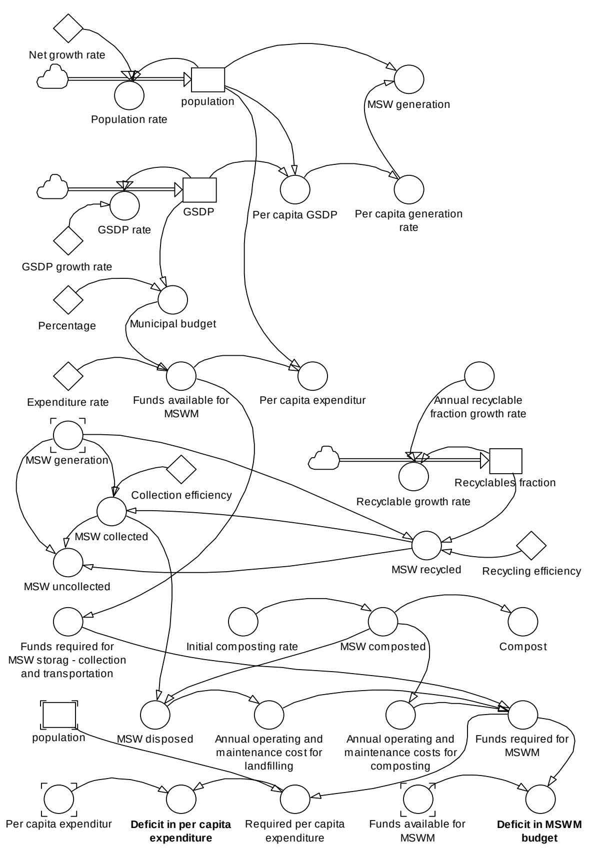

Fig. 5: Stock flow diagram of the existing MSWMS

4. RESULTS AND DISCUSSION

A system dynamics modeling showed that the population of Okhla increased from 1,25,474 on Jan 01 2001 to 1,48,195.83 on Jan 01 2010 with the growth rate of 1.87% per year as shown in Table 1. The generation of MSW increases from 8,124.86 t during 2001-04 to 1,0328.65 t during 2007-10 and per capita generation rate was 0.06 t/capita approximately during 2001-04 and it increases to0.07 t/capita during 2007-10 as shown in Table 2 and Table 3 respectively.

Table 1: Population of Okhla

Time	Population
Jan 01, 2001	
Jan 01, 2004	130,806.40
Jan 01, 2007	139,229.90
Jan 01, 2010	148,195.83

Table 2: MSW Generation in tons (t)

Time	MSW generation (t)
Jan 01, 2001	
Jan 01, 2004	8,124.86
Jan 01, 2007	9,160.72
Jan 01, 2010	10,328.65

Table 3: Per Capita MSW Generation rate in tons

Time	Per capita generation rate (t)
Jan 01, 2001	
Jan 01, 2004	0.06
Jan 01, 2007	0.07
Jan 01, 2010	0.07

Fig. 6 and Fig. 7 shows the nonlinear variation of MSW generation and Per capita MSW generation rate respectively.

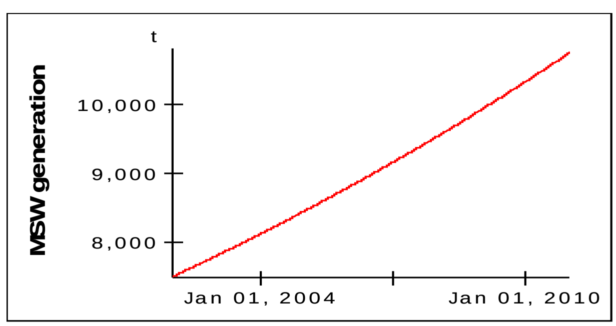

Fig. 6: Variation in MSW generation in ton (t)

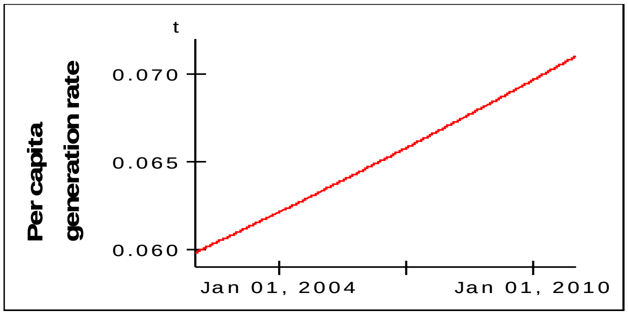

Fig. 7: Variation in per capita MSW generation rate in ton (t)

The MSW collected during 2001-04 was 5,961.11 ton which increased up to 6,622.80 ton during 2004-07 and further increased up to 7,338.39 ton during 2007-10 as shown in Table 4.The graph of MSW collected vs time is linear which shows the linear variation of MSW collected per year as shown in Fig. 8.

Table 4: MSW collection in tons (t)

Time	MSW collected (t)
Jan 01, 2001	
Jan 01, 2004	5,961.11
Jan 01, 2007	6,622.80
Jan 01, 2010	7,338.39

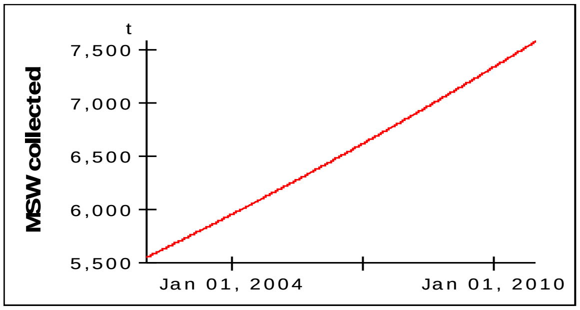

Fig. 8: Variation in MSW collection in tons (t)

The amount of MSW recycled during 2001-04 was 673.47 ton which increased to 882.22 ton during 2004-07 which further increased to 1,155.66 ton during 2007-10 as shown in Table 5.

Table 5: Amount of MSW recycled in tons (t)

Time	MSW recycled (t)
Jan 01, 2001	
Jan 01, 2004	673.47
Jan 01, 2007	882.22
Jan 01, 2010	1,155.66

The graph of MSW recycled vs time is nonlinear which shows the nonlinear variation of MSW recycled per year as shown in Fig. 9.

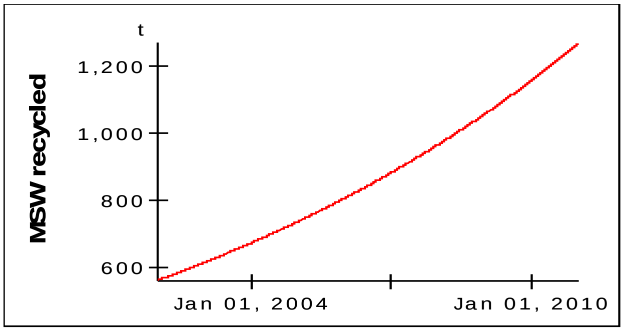

Fig. 9: Variation in MSW recycled in tons (t)

The amount of MSW disposed in landfill during 2001-04 was 4,711.11 ton which increased to 5,372.80 ton during 2004-07 and further increased to 6,088.39 ton during 2007-10 as shown in Table 6. The graph of MSW disposed vs time is nonlinear which shows the nonlinear variation of MSW recycled per year as shown in Fig. 10.

Table 6: Amount MSW disposed in tons (t)

Time	MSW disposed (t)
Jan 01, 2001	
Jan 01, 2004	4,711.11
Jan 01, 2007	5,372.80
Jan 01, 2010	6,088.39

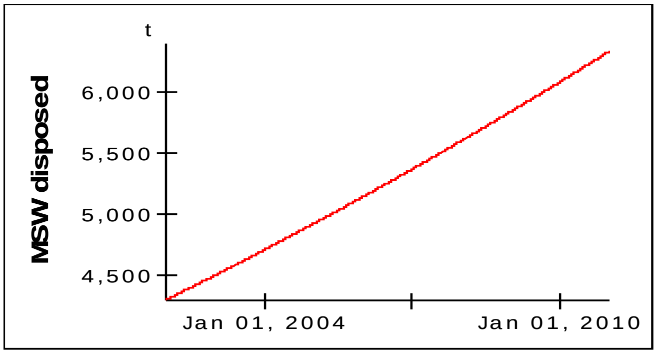

Fig. 10: Variation in MSW disposal in tons (t)

Table 7 shows the per capita deficit in budget. From the table we can see that per capita deficiency in budget during 2001-04 was Rs 22,786.00 which increased to Rs 23,783.70 during 2004-07 and the per capita deficiency in budget further increased to Rs 24,759.10 whose nonlinear graph is shown in Fig. 11.

Table 7: Per capita budget deficiency in Rs

Time	Deficit in per capita expenditure (Rs)
Jan 01, 2001	
Jan 01, 2004	22,786.00
Jan 01, 2007	23,783.70
Jan 01, 2010	24,759.10

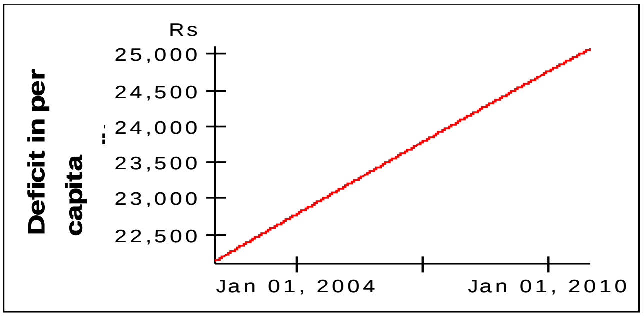

Fig. 11: Variation in per capita expenditure in Rs.

5. CONCLUSIONS

1. The Population of Okhla increased from 125474 on Jan 01, 2001 to 148,195.83 Jan 01, 2010 with the growth rate of 1.87% per year.
2. The generation of MSW was 8124.86 ton during Jan 01, 2001-04 and increased to 10328.65 ton during Jan 01, 2007-10.
3. Per capita generation rate was 0.06t/capita approximately during 2001-04 and it increased to 0.07t/capita in 2007-10.
4. The MSW collected during 2001-04 was 5,961.11 ton which increased to 6,622.80 ton during 2004-07 and further increases up to 7,338.39 ton during 2007-10 .
5. The amount of MSW recycled during 2001-04 was 673.47 ton which increased to 882.22 ton during 2004-07 and further increased to 1,155.66 ton during 2007-10.
6. The amount of MSW disposed in landfill during 2001-04 was 4,711.11 ton which increased to 5,372.80 ton during 2004-07 and further increased to 6,088.39 ton during 2007-10.
7. The per capita deficiency in budget during 2001-04 was Rs 22,786.00 which increased to Rs 23,783.70 during 2004-07 and further increased to Rs 24,759.10 during 2007-10.

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